Human optimization research: international activity

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Human Optimization Research

International Activity

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HUMAN OPTIMIZATION RESEARCH: INTERNATIONAL ACTIVITY

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1 EXECUTIVE SUMMARY

The present scientometric study was commissioned by the Chief Scientist Network of Defence Research and Development Canada (DRDC). It provides an overview of international research activity and collaboration networks in the field of human optimization. This is the second study in a series on human optimization, where the first was focused on the Canadian landscape.

To identify major players, their collaboration networks and key research topics in the international landscape, 7,656 references, dated 2005-2015, to relevant unclassified publications were retrieved and analyzed using text mining software and a variety of visualization tools. 114 research topics were categorized into five (non-mutually exclusive) metagroups including *Ethics, Physiological issues, Computational/Cognitive issues, Automation/Robotics* and *Means of Enhancement.* Internationally, research is most focused on *Computational/Cognitive issues*.

Visualizations of the 114 research topics showed great interconnection between them, displaying three main clusters; which speaks to the fact that research in this domain is quite interdisciplinary. Examining the research momentum of the topics reveals that 33 of the topics can be considered to be emerging (i.e. growing at a notable rate despite a relatively low publication count). While these emerging topics (e.g. *transcranial stimulation* or *neurophysiology)*, in and of themselves, are not necessarily emerging topics in the broader picture of scientific research, it may be that within the field of human optimization, these topics represent an emerging angle of research.

An analysis of the geographic distribution of the publications revealed that the US dominates the field in terms of total number of publications. However, Switzerland has both the greatest rate of collaboration (82%) as well as the highest average annual growth rate for 2012-2015 (70%). Most of the top countries are collaborating with each other. International collaboration networks are rather sparse amongst the top collaborating countries in that the top affiliations may have many different international colleagues but with very few repeated co-publications. Notable exceptions are described in the report.

Recommendations for further study include, among others, a formal comparison with the Canadian landscape, additional analysis of the *Means of enhancement* metagroup, and a deeper exploration of the top countries' collaboration networks.

Table 1. Key Findings

Key Question	Key Findings
Major International Research Topics	• Research on human optimization is predominantly occurring in *Computational/ Cognitive Issues* (6,039 publications) followed by *Physiological Issues* (5,176). A lower proportion of publications are focused on *Automation/Robotics* (3,183) and *Ethics* (2,976). • Top topics in the *Computational/Cognitive* metagroup include: *Performance (human/cognitive)*[a] (1,467), *Training* (1,171), *Simulation* (1,043) and *Interfaces* (1,027) • Top topics in the *Physiological* metagroup include: *Performance (general)* (1,440), *Optimization* (827), *Physiology (general)* (796) and *Brain* (622)

[a] *Performance (human/cognitive)* is distinguished from *Performance (general)* (in the *Physiological* metagroup) in that the keywords in the former are specifically related to human performance or cognitive performance, whereas those in the latter are related to performance in general, as in not in any specified way.

Key Question	Key Findings
	• Top topics in the *Automation/Robotics* metagroup include: *Robotics* (613), *Virtual Reality* (590), *Positioning & timing* (569) and *Sensors* (505) • Top topics in the *Ethics* metagroup include: *Military* (1,802), *Ethics* (562), *Gaming* (227) and *Adaptation (human)* (191) • A fifth metagroup was created to capture the *Means of Enhancement* as a way of further categorizing groups in the first four metagroups. Top topics include *Training* (1,171), *Learning* (891), *Human factors (engineering)* (861) and *Education* (574) • Research is emerging most notably in *Neurophysiology* (224), *Computer assisted surgery* (24), *Legal issues* (91), *Performance enhancing drugs* (46) and *Transcranial stimulation* (108)
Top International Researchers	1,102 international researchers have more than 3 publications, the most prolific are: ○ Hankey, J. (24), Virginia Polytechnic Institute, USA (*Computational/Cognitive*) ○ Scholey, A. (21), Swinburne University of Technology, Australia (*Physiological*) ○ Franke, A. (19), Johannes Gutenberg University, Germany (*Physiological*) ○ Redden, E. (18), US Army Research Laboratory GA, USA (*Computational/Cognitive*)
Top International Institutions	1,204 institutions have more than 2 publications and 25 have more than 30 publications. The most prolific institutes are all American, mostly military-based: ○ US Army Research Lab, Aberdeen Proving Ground, MD (145) ○ US Naval Postgraduate School, CA (110) ○ US Air Force Research Lab, OH (108) ○ NASA, CA (74) ○ Massachusetts Institute of Technology (62)
Top Countries	80 countries are found in the dataset, the most prolific are: ○ USA (4,278) ○ Germany (766) ○ UK (643) ○ China (513) ○ Canada (368) • The countries with the highest annual average growth rate in publications between 2012-2015 are Switzerland (70%), India (58%) and Hong Kong (32%)
Collaborations	• Switzerland (82.3%), Spain (81.8%) and Germany (63.5%) have the highest percent of papers with international institutions. • The majority of the top collaborating countries are collaborating with each other. Notable exceptions include the USA, Germany and the UK which have a broader range of collaborators. • Within the top four collaborating countries (based on total number of collaborations), very few of the top affiliations have collaborated with another institution more than once. Exceptions include: ○ Harvard University, USA with McGill University, CA (2) and Université Laval, CA (2) ○ University of Munich, Germany with University of California, San Diego (2) and University Utah, USA (2) ○ University of Oxford, UK with Delft University of Technology, Netherlands (3), Duke University, USA (2) and Stanford University, USA (2) ○ University College of London with University of Magdeburg, Germany (3) and Leibniz Institute of Neurobiology, Germany (2) ○ Swiss Federal Institute of Technology with Benemérita Universidad Autónoma de Puebla, Mexico (2) and University of Freiburg, Germany (2). • Many of the top affiliations in the UK and Switzerland share at least one collaborator in common, e.g. both the University of Oxford, UK and University of Cambridge have collaborated independently with Radboud University, Netherlands.

2 BACKGROUND

2.1 Context

The DRDC Director General for S&T (Army), together with the DRDC Office of the Chief Scientist, has commissioned a study to identify the international researchers in the field of human optimization and their areas of expertise, as well as map out their collaboration networks. A new Institute for Research Defence and Security (IRDS) has been approved for development by the Assistant Deputy Minister, Science & Technology for the Department of National Defence. The IRDS will consist of a number of Centres of Expertise in various defence S&T capability areas of interest and will bring together Canadian expertise, particularly from universities but also including industry. One such Centre of Expertise will facilitate research on human performance optimization for the IRDS and will facilitate two workshops that are being planned to bring together Canadian experts in the field.

Significant advances in human optimization have occurred in four directions: 1) cognitive enhancement as a computational issue, 2) performance enhancement as a physiological issue, 3) human effectiveness as an issue of automation, robotics & telepresence, and 4) ethics, including among other things, the bioethics of performance enhancement and the ethics of autonomous systems. Far from being disparate topics, DRDC's interest is to unify issues and communities in these four domains.

This study explores human optimization from a broad academic and technology-based perspective. A number of specific areas of interest are listed below and are explored within the bibliometric analysis.

Table 2. Client-Provided Metagroups and Associated Terms

Computational/Cognitive Issues	Physiological Issues	Automation/Robotics	Ethical issues
• Ubiquitous pervasive computing (ubicomp) • Low-power computing • Augmented reality • Neuromorphic computing • Position, navigation, and timing • Enhanced vision • Visualization of large information databases • Exobyte computing • Cultural Aids/ Automated machine translation	• Sleep-wake cycle • Circadian adjustment • Ergogenic aids • Countermeasure chemical, biological, radiological and toxic industrial material (TIM) agents • Gait efficiency and energy • Load carriage and soldiers • Load assistance • Exoskeleton and human • Human Behavior Patterns • Self-Decontamination Aids • Physiological enhancement/adaptation for extreme environments • Physical avatars • Brain/neuronal computer interface (BNCI) approaches for human optimization	• Robotics and telepresence • Telepresence and latency • Telepresence and remote • Effectors and telerobotics • Live virtual constructive and simulation • Wearable/Implanted Intelligent Sensors • Smart Armor • Smart Personal Intelligent Assistant (SIRI-like agent) • On-board facial recognition • On-board microclimate management • Wound sensing • Antimicrobial nanofibers for clothing	• Cultural lexicon • Serious gaming and training • Trust and autonomous systems • Autonomous systems and responsibility • Autonomous systems and Privacy • Social acceptance and legal considerations for human optimization

The analysis excludes research on rehabilitation, medicine, disease, aging, therapy, cancer, cognitive deficits/disorders, children or animals.

2.2 Key Issues

The objective of this second scientometric study on human optimization is to identify the international researchers in the field and to map out their collaboration networks. Results of this project will be used to further support DRDC effort on human system performance.

2.3 Key Questions

1. Who are the top 50 international researchers working in human optimization, where are they located and in which of the four sub-domains are they focused?
2. What are the top international affiliations in the field and what domains are they researching?
3. Which countries are collaborating internationally? Within the most active countries (top 4-5), who are the top affiliations collaborating with internationally?
4. Within each of the four main categories, which are the most active research areas?
5. Which topics are emerging?
6. Which countries have a greater rate of publication over the past 10 years, i.e. who has been increasing their publication rate over the last 10 years? List only those with a notable increase in the last few years.
7. Identify editorial boards of the top (10-15) journals and/or conferences.

3 INTRODUCTION

To address the key questions for this project, a broad search on human optimization was conducted in several bibliographic databases including *Scopus, Inspec, Compendex, NTIS,* and *PsychInfo*. The search resulted in a dataset of 7,656 unclassified publications.[b] In order to provide some context to the discussion on the collaboration networks, the report will begin with an overview of the research topics.

3.1 International Human Optimization Research Highlights

To identify research areas within the dataset, the terms in the keywords, abstracts and title fields were merged and 114 subject groups covering 7,313 publications (95% of the dataset) were created. Groups were first made by searching the dataset for the concepts listed in Table 2, followed by an analysis of terms that were not yet grouped. The groups, along with all the terms within them, were reviewed by the client and refined. When groups or terms remained in question, the associated titles and abstracts were reviewed by the client and analyst and final decisions were made regarding the groupings. The groups were further categorized into one of the four main metagroups by the analyst, and finalized by the client. A new, fifth group was created to capture the various means through which human optimization has been attempted and discussed in the literature.

Table 3 presents the five metagroups along with the number of publications in each. The total number of publications in the metagroups exceeds that in the dataset because a single article can be categorized in more than one group. This is particularly the case with the new *Means of Enhancement* group, since every group in this metagroup was first categorized in one of the others.

Table 3. Metagroups

Metagroup	No. of Publications	Scope Notes
Computational/ Cognitive Issues	6,039	Topics relate to cognitive enhancement as a computational issue, through technological support. These include, but are not limited to, computational aids to cognition such as enhanced mapping and location tools, logic engines, computation by social networking, and sensory enhancement.
Physiological Issues	5,176	Topics relate to performance enhancements through physiological changes to the body, through activities, drugs, physiological monitoring or modifications of human tissue.
Automation/ Robotics	3,183	Topics relate to the use of robots, devices and teleoperation to enhance human capabilities. These enable human operators to sense and act at indefinite distances. Such systems are often, but not necessarily, zoomorphic or anthropomorphic. The goal may be to control many systems at once, as in a swarm.
Ethics	2,976	Topics relate to the ethical issues regarding human optimization. Some topics expand our conceptual range to tools of human optimization that have only been promised as of yet.
Means of Enhancement	4,724	Groups include, for example, *Training; Human factors (engineering); Cognitive Enhancers; Biomechanics; Protective equipment, clothing; Haptic interfaces; Exoskeletons etc…* and capture the various means by which human optimization is being attempted or achieved.

[b] Classified publications were not included in this study, however there is classified work going on in the field.

Figure 1 presents the 114 subject groups, the total number of publications in each, along with the four main metagroups in which they have been categorized. This figure also reveals the most active research areas within each of the four metagroups. An Excel file with the same data is provided as Attachment 1 with this report.

Groups	Computational/ Cognitive Issues
Performance (human/cognitive)	1,467
Training	1,171
Simulation	1,043
Interfaces	1,027
Learning	891
Human factors (engineering)	861
Decision support	818
Imaging	639
Visual	636
Memory (human)	586
Education	574
Human Computer Interaction (HCI)	554
Detection	514
Target acquisition	448
Displays	435
Cognitive workload	431
Human System Interaction (HSI)	398
Recognition	378
Emotions	361
Intelligent systems & agents	341
Artificial intelligence	325
Situational awareness	314
Tracking	267
Mobile devices	260
Computer aided instruction	231
Augmented reality	225
Visualization	223
Computer vision	218
Facial recognition	211
Navigation	203
Embodied cognition	153
Magnetic resonance imaging	144
Augmented cognition	143
Ubiquitous computing	120
Brain Computer Interface (BCI)	113
Cognitive systems	112
Neural networks	110
Pattern recognition	81
Assistants (virtual)	75
Machine learning	69
Night vision	51
Aerospace Landing	49
Computer assisted surgery	24

Groups	Physiological Issues
Performance (general)	1,440
Optimization	827
Physiology (general)	796
Brain	622
Attention	618
Perception	583
Cognitive enhancement	484
Stress	482
Sleep/wake	393
Motion (human)	392
Human enhancement/ augmentation	368
Cognitive enhancers	362
Drugs (specified)	352
Performance enhancement	339
Movement	338
Exercise & fitness	317
Performance (task)	237
Ergonomics	232
Neurophysiology	224
Load carriage	204
Athletics/ sports	198
Muscles/skeletal	197
Nutrition, diet, supplements	194
Auditory perception	181
Stimulation (physical)	177
Gait & walking	159
Biomechanics	154
Protective equipment, clothing	151
Thermal adaptation	133
Stimulants (non-specified)	132
Biomed engineering/enhancement	124
Electrophysiology	111
Transcranial stimulation	108
Metabolism	107
Mobility	107
Exoskeletons	73
Circadian rhythms	54
Artificial body parts	47
Performance enhancing drugs	46
Endurance	44
Doping	38

Groups	Automation/ Robotics
Robotics	613
Virtual reality	590
Positioning & timing	569
Sensors	505
Adaptive systems	368
Optimization techniques	318
Video	306
Autonomous systems	303
Automation	281
Vision enhancement	276
Smart technology	189
Reaction time	129
Wearables	120
Teleoperation/presence	112
Haptic interfaces	97
Biotechnology	94
Sensing	94
Low power electronics	24

Groups	Ethics
Military	1,802
Ethics	562
Gaming	227
Adaptation (human)	191
Attitudes	190
Policy	176
Trust	109
Responsibility	100
Legal issues	91
Human optimization	82
Implants	71
Transhumanism	57

Figure 1. Subject Groups and Metagroup Membership

Figure 2 presents the subject groups that have also been categorized in the Means of Enhancement group.

Groups	Means of Enhancement
Training	1,171
Learning	891
Human factors (engineering)	861
Education	574
Human Computer Interaction (HCI)	554
Adaptive systems	368
Cognitive enhancers	362
Drugs (specified)	352
Exercise & fitness	317
Vision enhancement	276
Ergonomics	232
Computer aided instruction	231
Gaming	227
Nutrition, diet, supplements	194
Stimulation (physical)	177
Biomechanics	154
Protective equipment, clothing	151
Thermal adaptation	133
Stimulants (non-specified)	132
Biomed engineering/enhancement	124
Wearables	120
Brain Computer Interface (BCI)	113
Teleoperation/presence	112
Neural networks	110
Transcranial stimulation	108
Haptic interfaces	97
Assistants (virtual)	75
Exoskeletons	73
Implants	71
Night vision	51
Artificial body parts	47
Performance enhancing drugs	46
Doping	38
Computer assisted surgery	24

Figure 2. Subject Groups in Means of Enhancement Metagroup

In order to visualize the relationships between the groups, a cluster mapping was performed. sters are seen on the bottom left side.

presents a cluster map of the 114 subject groups based on a correlation matrix using cosine similarity. Cosine similarity is often used in information retrieval and text mining where terms are notionally assigned a different dimension and documents are characterized by a vector where the value of each dimension corresponds to the number of times that term appears in the document. Cosine similarly then gives a useful measure of how similar two documents are likely to be in terms of their subject matter. The technique is also used to measure cohesion within clusters in data mining. The correlation matrix shows a bi-directionally normalized (0 to 1) comparison of the relationship between two entities (subject groups) and shows the percentage of overlap between them. The cluster map was generated using TouchGraph Navigator[c] software, which identifies clusters based on 'Edge Betweeness Centrality'. Nodes within clusters tend to be close together while nodes in separate clusters are further apart. That being said, the proximity of nodes has been slightly altered to improve the readability of the map. TouchGraph's clustering algorithm ignores long edges that connect separate clusters, thereby splitting

[c] TouchGraph Navigator is produced by the US company TouchGraph LLC: http://www.touchgraph.com/navigator

separate connected components into the clusters that are shown.[d] This map has been filtered to show correlations of 27% or higher and contains 18 different color-coded clusters (outliers have been removed to increase viewing space). An image file of the full map is provided as Attachment 2 with this report. The three major clusters are circled and relate to visual enhancements (upper left), robotics and physiological enhancement (middle) and finally, cognitive enhancement and ethics (right). That so many groups are connected within these three clusters speaks to the fact that research in this domain is quite interdisciplinary and much of the research does not fit exclusively in any of the four metagroups presented in Table 3. Four additional smaller clusters are seen on the bottom left side.

[d] For more information on the clustering algorithm used by TouchGraph Navigator please see http://www.touchgraph.com/assets/navigator/help2/module_7_7.html?MenuState=AUdAAO-0hAHvtIQABO-0hO-0gwAZAQPvtIRjbHVzdGVy

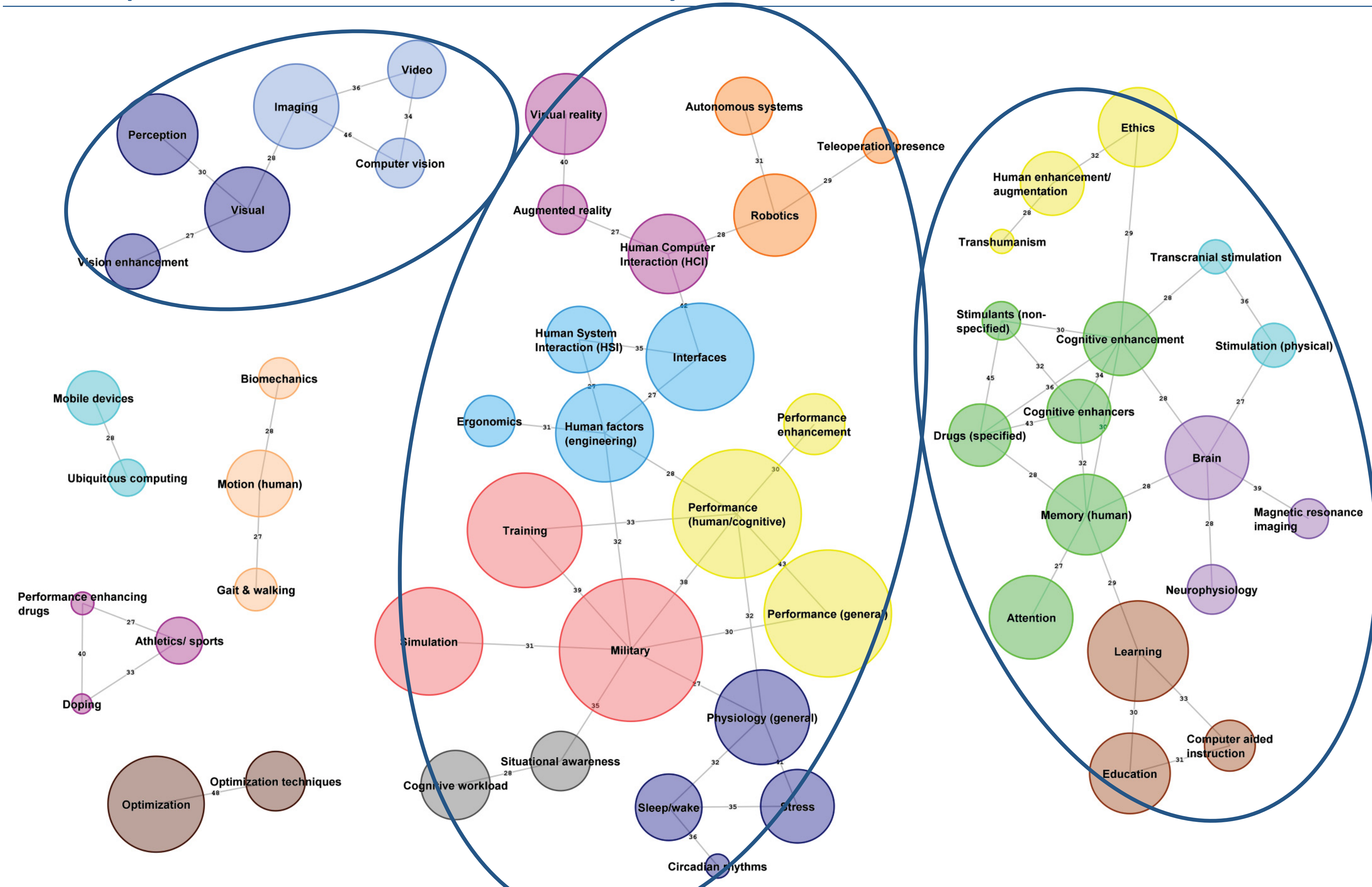

Figure 3. Research Clusters

3.2 Emerging Research

Although a count of publications within each subject group (as per figures 1 and 2) provides some insight into the quantity of research activity on a given topic, it does not sufficiently convey the momentum of a topic relative to others in the same set of data. In other words, the quantity of records in a group does not necessarily suggest which topics are "hot", which are fading and which are emerging. For topics in the literature, the determination of momentum is based on the relative velocity of each subject group in the dataset between 2010 and 2015. Further explanation of the methodology behind the momentum indicator is included in Section (0), but essentially it plots the standard deviation of standardized measures of publication counts and velocity (the rate of publication increase) on two axes. Nodes which plot to the left of the Y-axis intersection have below-average velocity, and those found below the X-axis have relatively smaller publication counts. A third dimension is added by sizing nodes relative to the total number of underlying publications. Even a small node which plots to the right/lower side of the axes may be of interest, since emerging topics are typically small in numbers as they begin to attract research attention and increase in velocity. The full R&D Momentum chart is provided in Attachment 3.

Figure 4 shows the 33 groups that fall into the Emerging quadrant, 11 of which are categorized in the *Computational/Cognitive* metagroup, four are categorized in *Automation/Robotics,* six are in the *Ethics* category, 12 are in *Physiological*, and 13 are also grouped in *Means of Enhancement.* A description of the groups with a higher than 1.5 z-score growth rate[e] including *Neurophysiology, Computer assisted surgery, Legal issues, Performance enhancing drugs* and *Transcranial stimulation* is presented below.

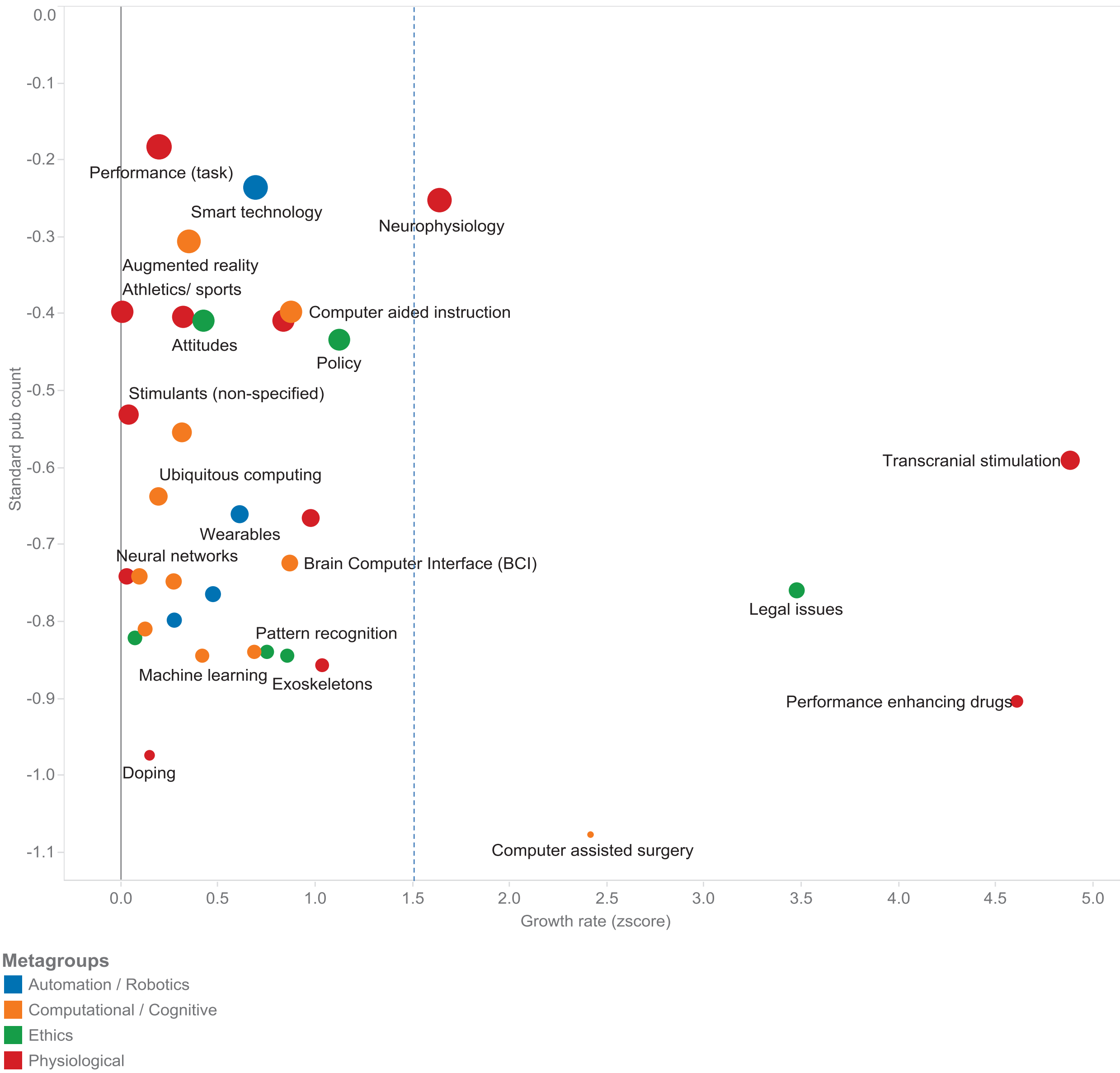

Figure 4. R&D Momentum: Emerging Research Topics

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[e] This cut-off point was selected by the client after reviewing the results.

Neurophysiology

The *Neurophysiology* group has 152 articles over the past five years, 72% of which have an affiliation from the USA and 35% have an affiliation from Germany.[f] The field of human optimization uses neurophysiology to better understand the functioning of the human nervous system and brain, in order to either directly improve human performance or to improve other systems that help optimize human performance.

Some of the articles in this group talk about using neurophysiological processes to measure and thus improve learning, training and performance outcomes.[1] For example, one study examined changes in the lead-lag relationship between team communication (quantified using latent semantic analysis) and team neurophysiology (quantified using a neurophysiologic synchrony method) as a function of training in submarine crew members.[2] Another study used EEG and ocular data to classify operator states in terms of working memory capacity, in order adjust training difficulty to improve learning.[3] Neurophysiological markers (e.g. eye scan metrics) have also been used to improve the design of simulation to be more responsive to individual traits in training for continuous complex cognitive tasks.[4] In a final example on the use of neurophysiological processes to measure and improve performance, a study used a combination of classifiers of neurophysiological biomarkers, subjective assessments of perceived cognitive workload and task performance to assess pilots' levels of attention during challenging flight simulation exercises. The findings of that study were used as the conceptual basis for developing a real-time cognitive state monitoring tool that facilitates adaptive human-computer interaction in operational environments.[5]

Many of the studies used neurophysiological data to improve human-computer interaction (HCI), brain-computer interaction (BCI) and augmented cognition. Optical brain imaging such as functional near-infrared (fNIR) spectroscopy has been used to assess user experience with synthetic speech systems to improve their development, as they are increasingly being integrated into human-computer interaction and automated systems with the emergence of ubiquitous computing.[6] fNIR has also been used to study expertise acquisition during simulated flying missions.[7] One of the challenges with using neurophysiological cognitive state assessments in the design of augmented human-machine systems is that pattern classifiers can be unstable over time (hours and days). One study proposed new methods for 'learning' non-stationarity to help develop more generalized and stable patterns.[8] The development of a multi-channel wireless wearable surface electromyography and fNIR acquisition system has also been used to enhance human-computer interaction to provide more information about muscle activity of the wearer and thus the subject's motor intentions.[9] By understanding the underlying neurophysiology of multisensory processing, the neuroergonomics of multisensory machine interface and analytical methods for neural signal analysis, dimensionality reduction and pattern recognition, new opportunities are emerging for the creation of advanced military human-computer interfaces and displays that will augment soldier performance.[10]

Computer assisted surgery

The *Computer assisted surgery* group has 11 articles in the last five years, 45% have an affiliation from USA and 18% have an affiliation from Germany and 18% have an affiliation from China. Computer assisted surgery includes the use of surgical robots, teleoperated manipulators, image-guided robots and the like, to support surgical procedures. Teleoperated manipulators are designed to enhance human

[f] The combined affiliation percentages can exceed 100% as these counts are based on the number of publications each country is listed on and does not take into account the presence of any other countries (i.e. collaborations).

cognitive and physical skills, while image-guided robots are designed to surpass human limitations by providing automated targeting and treatment delivery methods.[11]

A number of the articles present various systems that are currently under development such as an intelligent surgical robotic system designed to enhance hand-eye coordination using adaptive visual and haptic cues,[12] or a micro-manipulator for middle ear surgery which results in a significant reduction in number of errors and time during simulated surgeries.[13] Others report on research that is advancing or improving existing systems such as the use of near infrared brain-computer interfaces as a complementary input modality to enhance human-robot interaction at medical robotic consoles,[14] or better alignment between haptic devices and visual displays in order to create more accurate simulation and interaction in virtual reality surgical systems.[15]

According to a 2011 BCC Research report, the global market for medical robotics and computer-assisted surgical equipment was worth nearly $2 billion (USD) in 2010 and was projected to grow to $3.6 billion (USD) by 2016.[16] Thus the low number of articles in this group is most likely a function of the broader computer assisted surgery field not presenting their research in terms of human enhancement, rather than an accurate reflection of the research volume or velocity in the field.

Legal issues

The *Legal issues* group contains 66 articles that look at legal aspects and issues related to cognitive enhancement and cognitive enhancers (i.e. drugs) including issues related to illegal drug use. A total of 33% of the publications come from USA, 18% from Germany and 16% from UK.

Many of the articles note, in a general fashion, that there are legal issues alongside the social, philosophical, medical and ethical issues related to human enhancement.[17-19] Those that go into more detail explore a variety of issues, such as the potential negative situation in which the law may pressure people to take cognitive enhancing drugs by offering a choice of (accompanied by indirect pressure to) accepting medical treatment or suffering a legal disadvantage.[20] This concern was viewed as a potential impact for those in high-responsibility professions, such as surgeons and pilots, where using biomedical enhancers may ultimately be imposed in order to minimize adverse and maximize positive outcomes in these fields.[21] On the flip side, it has been argued that although competition over jobs and goods might coerce people to use biomedical enhancements, a proper legal framework would help address this concern. However, the author then goes on to consider circumstances under which it would still be justified to use incentives and penalties to non-coercively induce people to use biomedical enhancements.[22]

A number of the articles also look at regulatory issues. One proposes a case-by-case (i.e. each drug) approach to legal regulation and concludes, for example, that a moderately liberal, permissive regulatory approach to extended release forms of methylphenidate would be appropriate, but would not apply to amphetamines nor instant release forms of methylphenidate. Another explored the various German judicial perspectives on three kinds of biomedical enhancers (over the counter, prescription and illegal) and noted that the direction of upcoming regulation and policy development will likely depend on the availability of such drugs, individual and society implications of their use and public opinion.[23] Regulations, at an international level, are called for to manage privacy and autonomy issues with the advancement of bioelectronics and nanotechnologies used in brain-machine interfaces.[24] Finally, it has been put forth that the interplay between values and external factors (including regulations) is what lies at the heart of the controversy and ethics of cognitive enhancement.[25]

Performance enhancing drugs

The *Performance enhancing drugs (PED)* group has 41 articles, 54% of which relate to the use of (legal) performance enhancing drugs in athletics or sports and 39% discuss doping (illegal or banned performance enhancing drug use). 29% of the articles are from the USA, 24% from the UK, and 20% from Germany.

Many of the articles in the *PED* group explore the attitudes of various populations toward the use of performance enhancing drugs. Overall, there appears to be at least two views on, and attitudes about, the prevalence of PED use. On the one hand, there are the authors who view PED usage as an emerging and growing public health threat that has remained largely unrecognised,[26,27] while others recommend that academics, the media and regulators avoid making more exaggerated claims about PEDs and their usage than the evidence suggests.[28]

Population group attitudes ranged from excusing the practice, to fearing it, to more generally opposing it. A US study explored the attitudes of professional cyclists and team personnel regarding PED use and found that a variety of “neutralization techniques” are used to justify and excuse PED usage.[29] This same author also reported in another study that the continued anxiety regarding the proper role of PED in modern society will likely lead to further reactive and punitive responses to PED use.[30] Finally, an Australian survey found that policies that facilitated the use of performance enhancing drugs, for sport or cognitive enhancement, would be at odds with public attitudes.[31]

In addition to studying the use of performance enhancing drugs in the field of sports, PEDs have also been studied in academic settings, where the motivations from PED use is the focus of most studies. A survey of German university students’ use of performance enhancing substances ranged from 1-13% taking prescription or illegal drugs to support concentration, to relax or increase alertness, with significant gender differences with regards to frequency and reason.[32] While one study found that test anxiety increases the use of prescription medication for cognitive performance enhancement,[33] another discovered that the motivation for using PEDs is broader and reflects a belief that they are advantageous for leading an active life with a reasonable balance between studying and time off.[34] While many students believe in the cognitive enhancing capacity of PEDs, the evidence for cognitive or academic gain from PED use is weaker than the evidence for physical performance gains in the sporting domain.[28,34-36]

While few articles specified which drugs or substances were being used, those that did found that Choline results in enhanced neural efficiency[37] and oral consumption of nicotine can improve the consolidation processes in perceptual learning.[38]

Transcranial stimulation

The *Transcranial Stimulation (TS)* group has 92 articles and covers such approaches as transcranial magnetic stimulation (TMS), transcranial direct current stimulation (tDCS), transcranial alternating current stimulation (tACS), deep brain and brain depth stimulation and the more general non-invasive brain stimulation (NBS). 41% of the articles are from the USA, 24% from the UK, and 15% from Canada.

As recently as 2014, authors have described the use of transcranial stimulation (TS) as a new line of research, with recent advances and implications for the enhancement of human cognition in general and memory in particular.[39,40] Non-invasive brain stimulation has increasingly been investigated in experimental neuropsychological studies with healthy volunteers due to its low cost, ease of use, safety, portability and significant effects on working memory, decision-making, and language.[41] TS, and specifically TMS, has been found to have an enhancing effect through either the direct modulation of a particular region in the brain, leading to more efficient processing, or through the disruption of other processes which competes or distracts from specific task performance.[42] However, because the use of TS for human enhancement is so new, the underlying mechanisms of the performance improvement, the potential cost or side effects, and the effects of different individual traits on stimulation outcomes are still being explored.[43-45]

Some of the research discusses TS from a high level, focusing only on the areas of performance that are enhanced or exploring gaps in knowledge (as described above), while other articles discuss the impact of stimulation of specific regions of the brain (e.g. dorsolateral prefrontal cortex, right inferior frontal cortex, left anterior temporal lobe) on specific cognitive functions (e.g. response inhibition, task switching, memory updating).[46,47] Still other research focuses on the ethical issues. The use of non-invasive brain stimulation techniques for cognitive enhancement has ethical issues, much like pharmacological enhancement, that must be considered.[48] One article presents a modified ethical parity principle (EPP), which is seen as the most prominent moral principle that is specifically designed for resolving ethical issues related to neurological modification (of which TS is a form).[49] TS has also been evaluated against five common objections to the use of cognitive enhancements (in general), including safety, authenticity, cheating, social justice and positional goods and it was concluded that TS practices are not negatively influenced by any of them.[50] A final critical aspect of TS ethical issues is the call for regulation of cognitive enhancement devices (for tDCS),[51] potentially under medical devices legislation, in order to manage the purchase and building of such devices by private individuals for home use.[52]

3.3 Top International Researchers

Over 19,000 international researchers appeared in the dataset; of these, roughly 1,100 have at least three publications. The top international researchers, with 16 or more publications, are presented in Figure 5 along with their affiliation and total number of publications. The top 2-3 groups in which their publications have been grouped, along with the metagroups in which the authors' works have been categorized, is also provided. The combined total of publications in each metagroup exceeds the author's total number of publications because a single publication may be categorized into a number of metagroups. For example, Savelescu, J.'s 2014 article "Pharmacological cognitive enhancement—How neuroscientific research could advance ethical debate" has been grouped (based on keywords) into *Policy, Memory,* and *Exercise & fitness* which each fall into the *Ethics, Cognitive/Computational and Physiological* metagroups. The majority of the top authors presented below are from the US, the remainder are from Australia, Germany and the UK. 36% of these most prolific authors are publishing on robotics.

A complete list of all authors with nine or more publications, along with their complete contact information and areas of expertise is included with this report as Attachment 4.

Top Authors	Total # Publications	Top Groups	Computational/ Cognitive Issues	Physiological Issues	Automation/ Robotics	Ethics	Means of Enhancement
Hankey, J. (Virginia Polytechnic Institute, USA)	24	Human factors engineering; Night vision	24	9	10	7	23
Scholey, A. (Swinburne University of Technology, Australia)	21	Drugs; Memory; Performance (Cognitive/Human)	19	21	3		19
Franke, A. (Johannes Gutenberg University, Germany)	19	Stimulants; Drugs; Attitudes	14	19	1	10	19
Redden, E. (US Army Research Laboratory, GA)	18	Performance (General); Robotics	18	16	15	17	15
Barnes, M. (US Army Research Laboratory, AZ)	17	Robotics; Autonomous systems	17	14	16	15	14
Berka, C. (Advanced Brain Monitoring, Inc, USA)	17	Neurophysiology; Training	16	14	5	8	13
Chen, J. (US Army Research Laboratory, FL)	17	Robotics; Autonomous systems	17	15	16	13	14
Cosenzo, K. (US Army Research Laboratory, MD)	17	Autonomous systems; Robotics	17	13	14	15	13
Lieb, K. (Johannes Gutenberg University, Germany)	16	Stimulants; Drugs; Attitudes	11	16	1	9	16
Parasuraman, R. (George Mason University, USA)	16	Performance (Cognitive/Human); Adaptive systems; Automation	16	16	10	10	15
Savulescu, J. (University of Oxford, UK)	16	Ethics; Cognitive Enhancement	8	16	1	14	12

Figure 5. Top Authors, Areas of Expertise

3.4 Top International Affiliations

Figure 6 presents the top international affiliations with over 30 publications. The majority of the top institutions are from the USA and many are military or NASA organizations. Two affiliations from the UK and the Netherlands affiliations, along with one each from Canada and France are included in the list. The Max Planck Institutes in Germany also have a combined total of 30 publications, but the institutions were not merged into one affiliation and thus do not show up in this figure. An Excel sheet with the top affiliations and the top groups and metagroups in which their research is categorized is provided as Attachment 5 to give insight into their research domains.

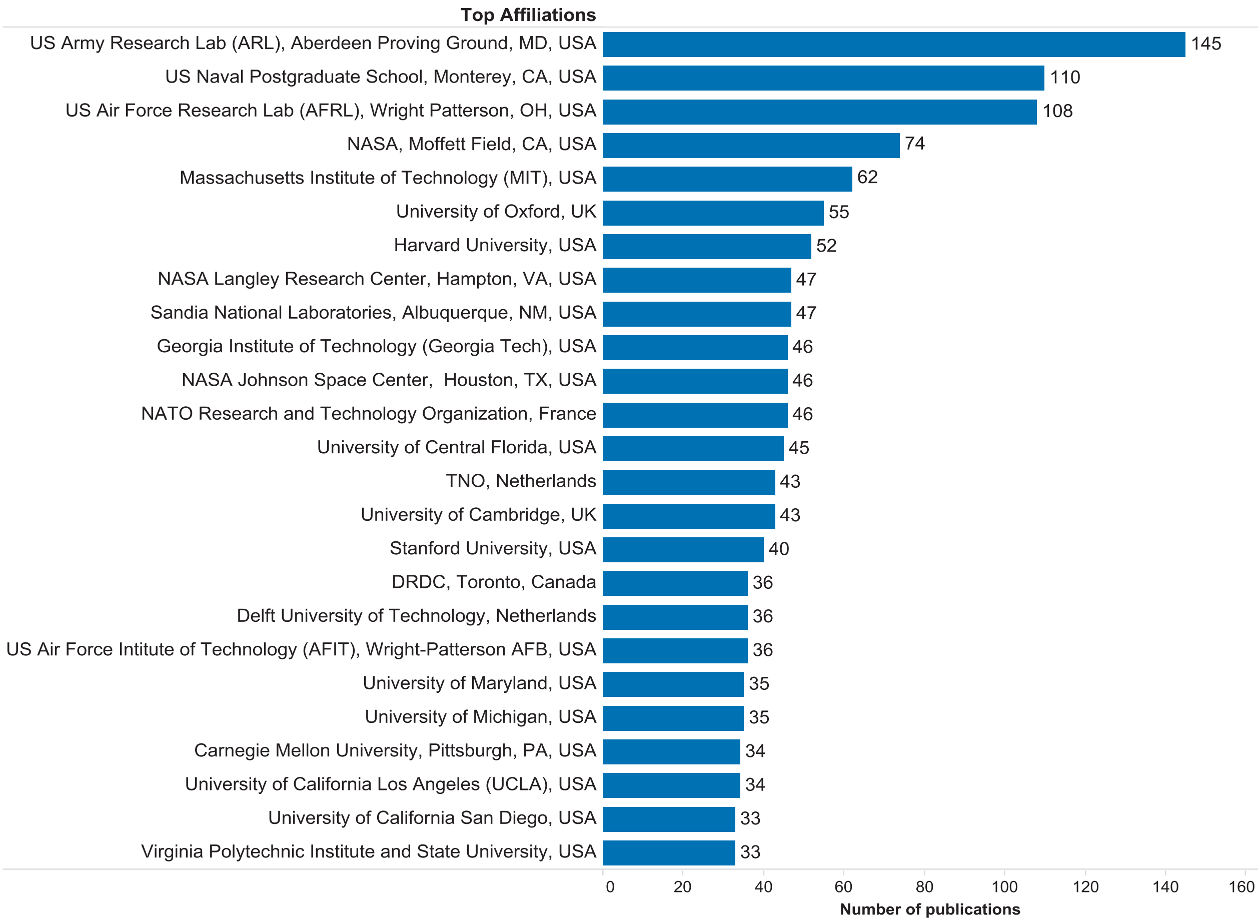

Figure 6. Top Affiliations

3.5 Top Countries and Growth Rates

Records in the dataset are affiliated to a total of 80 different countries with more than 1 unclassified publication. The top 10 countries all have at least 200 publications, with the USA publishing far more than Germany, the second most prolific country. The total number of publications for the top 20 countries is presented in Figure 7.

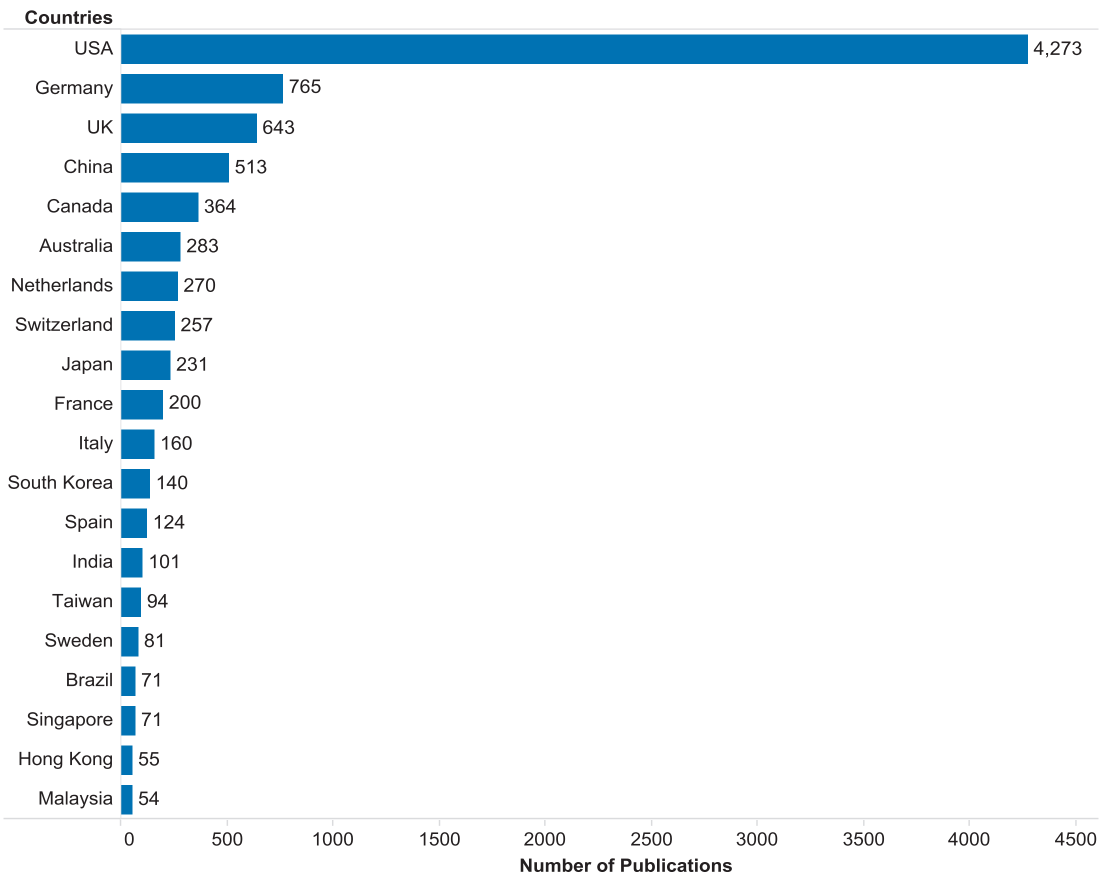

Figure 7. Top 20 Countries

Figure 8 shows the average annual growth rate (AAGR) for 2012-2015[g] for the countries with the highest average growth in publications. Switzerland, India and Hong Kong have each increased their publication rates by more than 30% in the past 3 years. In fact, Switzerland has the highest AAGR across the whole 10 year period. Italy, Netherlands, and Australia have also increased their publication rates by at least 20%.

	AAGR (2012-2015)
Switzerland	70.3 %
India	58.0 %
Hong Kong	32.3 %
Italy	25.8 %
Netherlands	25.7 %
Australia	24.3 %

Figure 8. Top Country Publication Growth Rates

3.6 Top Collaborating Countries

The countries with a minimum of 100 international collaborations are presented in Figure 9 along with their absolute number of collaborative papers and the percent of these papers on which they collaborated internationally. This data is calculated by counting the total number of papers that have been co-authored with *other* countries (that had at least 3 publications in the dataset). The countries are ordered by total number of collaborative papers and shaded by percent of collaborative papers. While the USA has the highest total number of collaborative papers, Switzerland, which is closely followed by Spain, has the highest percent of international collaborative papers.

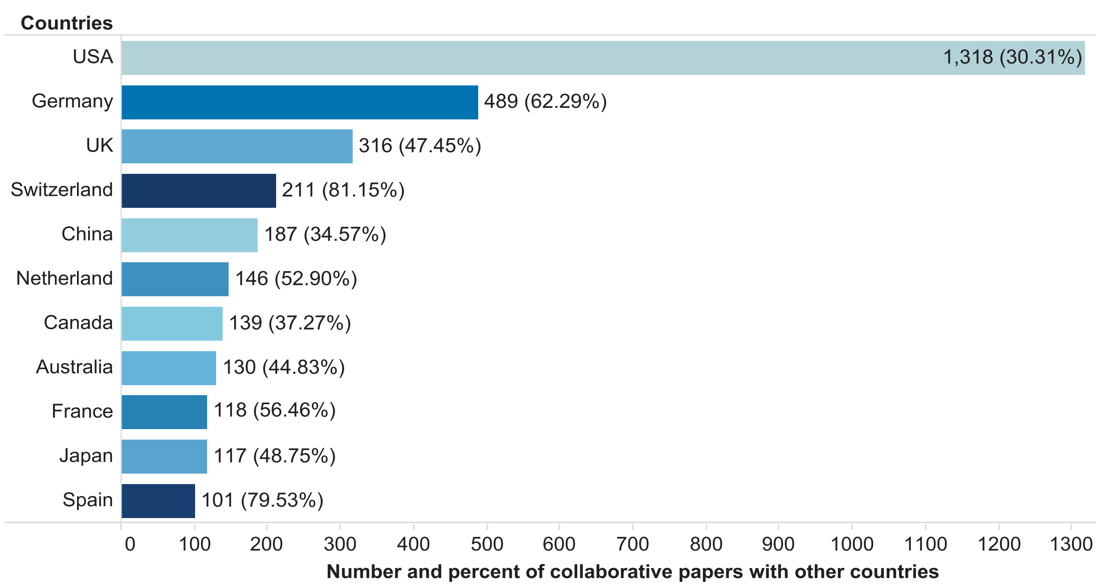

Figure 9. Top Collaborating Countries

[g] Average Annual Growth Rate was calculated by taking the average of the growth rates [Growth rate = (Ending Value - Beginning Value) / Beginning Value)*100] for the period of 2012-2015. This period was chosen to identify those countries with a recent notable growth rate. Incidentally, the top three rankings are the same for 2010-2014.

Figure 10 presents the other countries with whom the top 11 collaborating countries are collaborating. The top collaborating countries are listed on the top, in order of the percent of collaborative papers they each have. The international collaborators, on the left, are listed in order of the total number of collaborations they have in the dataset. The international collaborators are limited to those with at least five collaborative papers. The majority of the 11 top collaborating countries are collaborating with each other. Notable exceptions include the USA, Germany and the UK which have collaborations with a broader range of countries. An Excel sheet with this data is provided as Attachment 6.

Top Collaborating Countries

International Collaborators	Switzerland	Spain	Germany	France	Netherlands	UK	Australia	Canada	China	USA
USA	133	86	279	89	70	137	50	104	101	
Germany	27	20		20	40	43	11	22	18	279
UK	18	8	43	9	17		44	11	17	137
Switzerland		10	27	5	6	18		8	12	133
China	12		18		5	17	9	7		101
Canada	8		22	9	6	11	9		7	104
Netherlands	6	6	40	6		17		6	5	70
France	5	3	20		6	9		9		89
Spain	10		20	3	6	8				86
Australia			11			44		9	9	50
Japan	8		15		5	9			13	68
Italy	8		16	9	7	17				56
South Korea			10			5				48
Brazil						6				42
Belgium			7		9	10				17
Singapore			7			5			5	26
Sweden			11			7				22
Taiwan			6			8				20
Hong Kong									21	14
Austria	7		11							7
Portugal			5							20
India										20
Finland			5			7				10
Malaysia						5				16
Ireland			6			6				7
Denmark						4				11
Poland			6							14
Mexico										19
Greece			5			8				5
Argentina										13
Israel										12
Romania										12
Hungary										9
Chile										9
Iran										8
Turkey										9
New Zealand										7
Norway										6
Thailand										6
Colombia										5
Pakistan										5
Saudi Arabia										3

Figure 10. Collaborating Countries Matrix

3.6.1 Top Countries' International Collaborations

The following section presents visual diagrams of the international collaborations within the top four countries (selected by total number of collaborative papers). Only repeat collaborations (those that have occurred between the same two affiliations) and those that are shared between top affiliations (e.g. two top affiliations with a single international affiliation) are described below. The maps only reveal collaborations between the top institutions and their international collaborators and do not show the collaborations between those international collaborators. As such, while a single paper may include collaboration between a top affiliation and multiple international affiliations, the connections between the international affiliations do not show up on the map. As appropriate, these will be mentioned in the sections that follow.

3.6.1.1 United States

The top four US affiliations by total (unclassified) publication count include US military labs or schools and Sandia National Laboratories, none of which have much international collaboration and none that occurred more than once. As such, the next five most frequent affiliations, all of which are universities, have been included in the maps below. The top nine US affiliations have 682 publications, 124 with collaborations, 37 of which have international collaborations with 77 different international collaborators. Figure 11 presents a list of the top US institutions with their number of international collaborators. The combined total of the international collaborators is higher than 77 as more than one institution has collaborated with the same international collaborator. This is particularly the case the US Naval Postgraduate School and the US Air Force Research Lab which have both collaborated with the National University of Ireland.

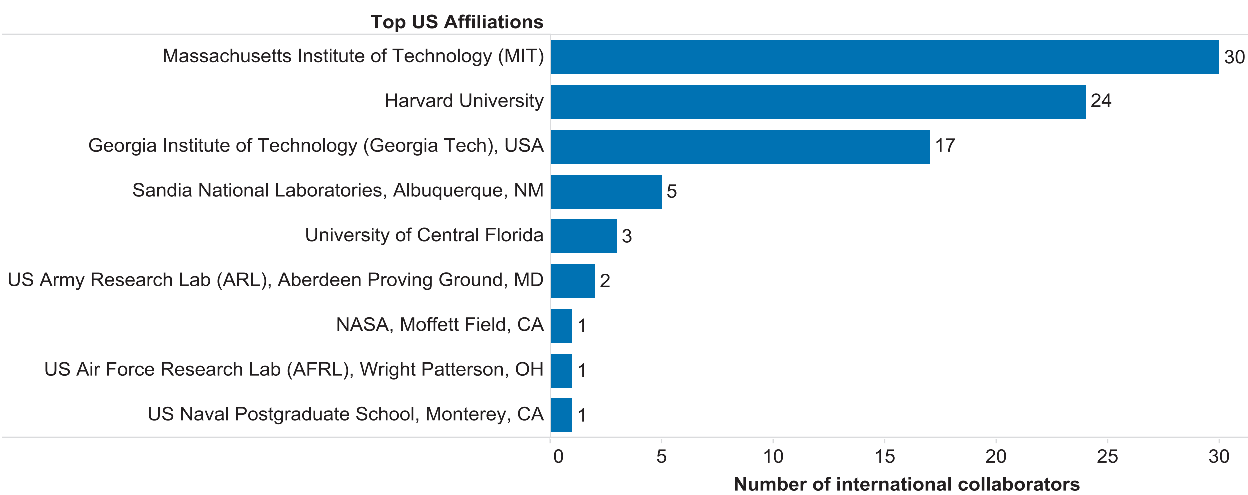

Figure 11. U.S.A. Top Affiliations, Number of International Collaborators

Figure 12 presents a visual map of the top US institutions' international collaborators. The number on the lines (edges) shows the number of co-publications between institutions, while the numbers in the green boxes (legible in the attached png file) shows the total number of publications for each institution. Once again, only direct connections to the US affiliations are shown and connections between international affiliations that have collaborated together on a single paper with a US affiliation do not show up on the map. The image file and the supporting raw data file are provided as Attachments 7 and 8 with this report.

Only Harvard University has collaborated with the same institutions (McGill University and Université de Laval in Canada) more than once. Harvard University and McGill University co-published a paper on the characteristics of distraction that lead to impairment or enhancement of performance.[53] Harvard University and Université de Laval collaborated with the University of Lyon, France on an article about the use of non-invasive brain stimulation (NIBS) to enhance motor and cognitive performance and its potential use for improving training for military, civil and forensic security services. This paper also touches on the ethics of using NIBS on healthy individuals.[54] Harvard University has also collaborated with McGill University and Université de Laval on an article that showed that pain expressivity in chronic pain patients increased the vicarious brain responses and the sensibility to others' pain.[55]

Interestingly, only the US Naval Post Graduate School and the US Air Force Lab, Wright Patterson, have collaborated with the same international affiliation. Both were co-authors on a single paper with the National University of Ireland which found that stress training during flight training may serve to enhance pilot performance during stressful operational flights and might mitigate the contribution of pilot stress to aircraft mishaps.[56]

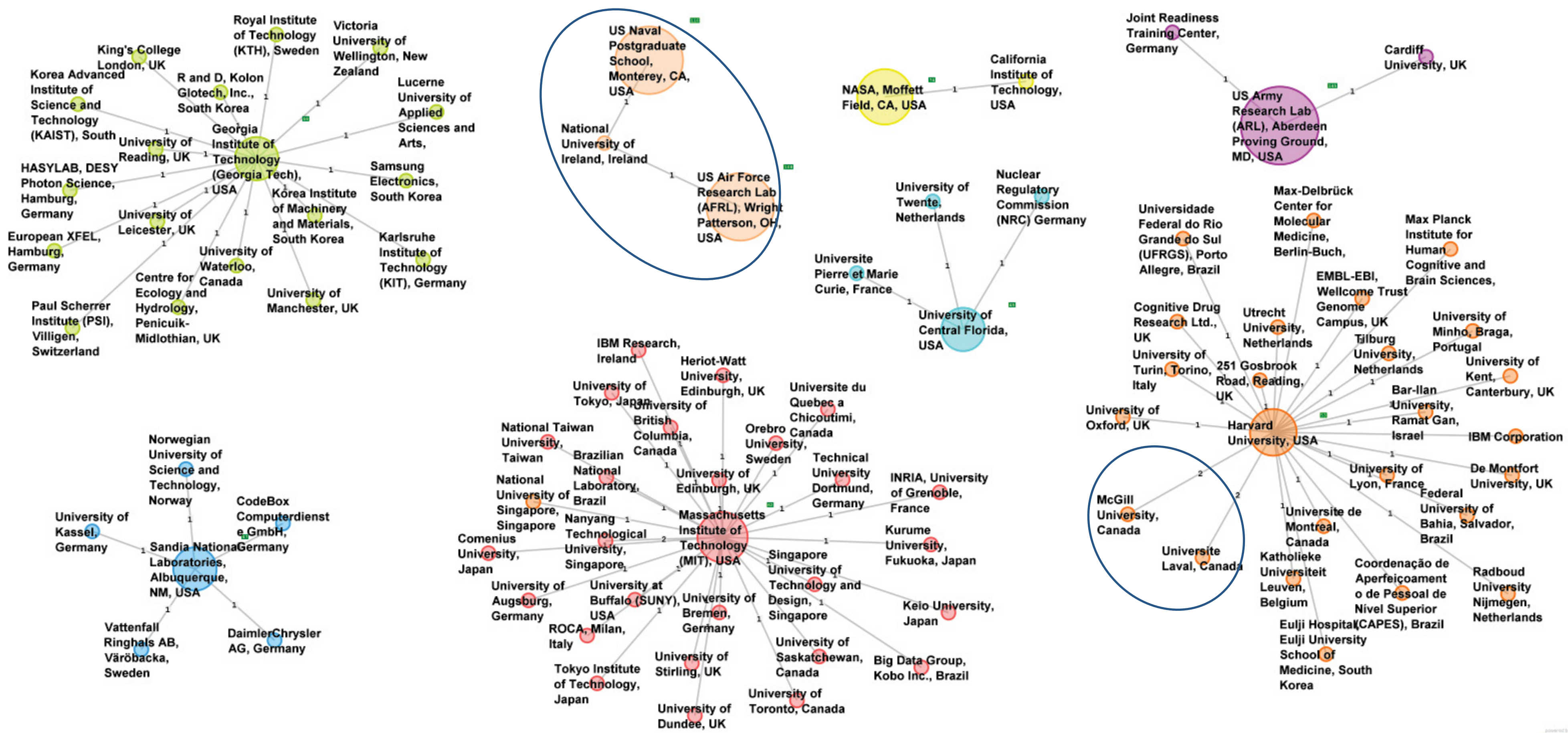

Figure 12. U.S.A: Top Affiliations, International Collaborations

3.6.1.2 Germany

The top five German affiliations have 85 publications, 50 with collaborations, all of which are with 41 different international collaborators. Figure 13 presents the number of international collaborators for each of the top five German affiliations.

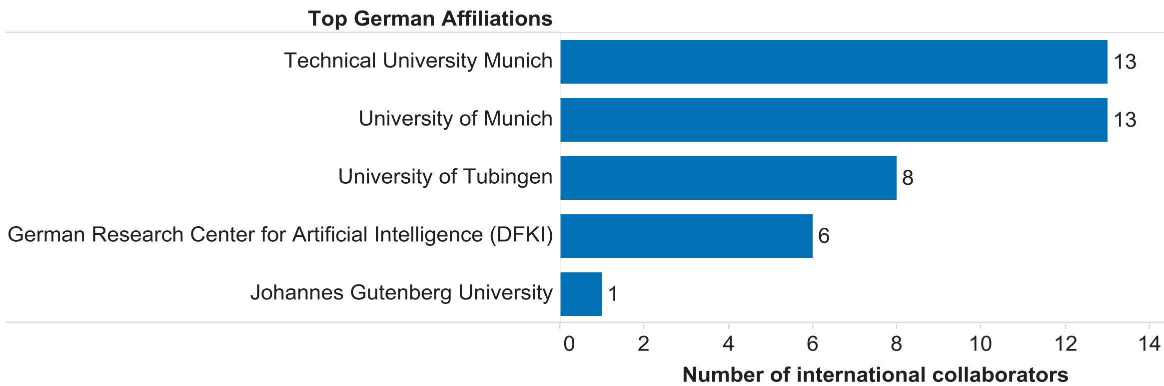

Figure 13. German Top Affiliations, Number of International Collaborators

Figure 14 we see that each of the top German affiliations has their own independent collaboration networks. Only the University of Munich has any repeat collaborations, including two shared co-publications with the University of Utah and University of California, San Diego, USA from 2007 and 2009. These two papers looked at improved modeling of the skull and the cerebrospinal fluid compartment and evoked potential data with high signal-to-noise ratio (SNR) that can be used for the analysis of clinical or cognitive data.[57,58] The image file and the supporting raw data file are provided as Attachments 9 and 10 with this report.

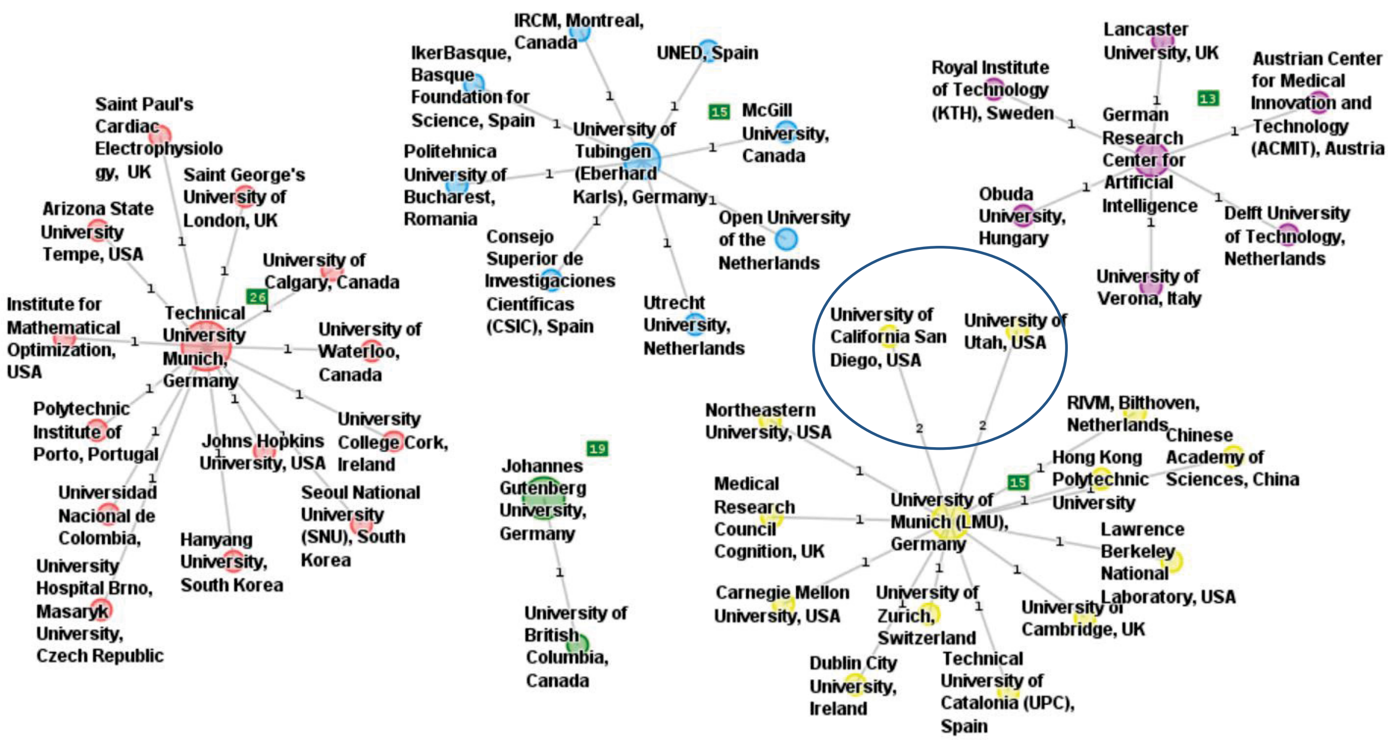

Figure 14. Germany: Top Affiliations, International Collaborations

3.6.1.3 United Kingdom

The top 5 UK affiliations have a total of 148 publications, 61 co-authored with another institution, 50 of which are with 104 different international collaborators. Figure 15 presents the number of international collaborators for each of the top five UK affiliations.

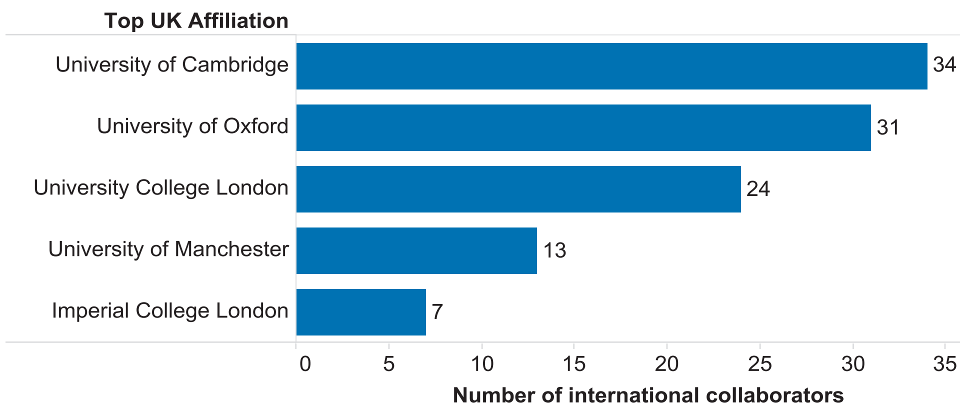

Figure 15. UK Top Affiliations, Number of International Collaborators

Figure 16 presents the networks for the University College of London, University of Cambridge and University of Oxford. Only the University of Oxford and University College of London have repeat collaborators. The image file and the supporting raw data file are provided as Attachments 11 and 12 with this report.

The University of Oxford has collaborated on three unique papers with Delft University of Technology, Netherlands, in the past two years. Two publications from 2014 reviewed attitudes toward pharmacological cognitive enhancement (PCE) [59] and whether the development of PCEs might result in imposing new duties on people in high-responsibility professions such as surgeons or pilots.[21] The 2015 publication extends the discussion on new duties by presenting a theoretical framework and multidisciplinary methodology for investigating the claim that some professions might have a responsibility to use PCEs to enhance their professional performance.[60]

The University of Oxford has collaborated on two unique papers with Duke University, USA about human enhancement in courtrooms. The first is a book chapter from 2012 that reviews the beneficial and detrimental effects of biomedical interventions on cognition, with a focus on its use by lawyers, judges and jurors during long court proceedings.[61] The second is another book chapter that compares jurors' use of external aids (such as notetaking) with biomedical aids (i.e. cognitive enhancement drugs) and argues that any biases introduced by the drugs should be considered acceptable.[62]

Finally the University of Oxford collaborated on two papers with Stanford University. The first from 2010, which included authors from Potomac Institute for Policy Studies, Georgetown University and University of California, Santa Barbara, all from the USA, discusses the implications of new neuro-technologies and their accompanying paradigms of human enhancement and transhumanism on the basic self-perception of what a human being is.[63] The second publication, from 2013, also included authors from the University College of London, UK and presents findings that show that the use of transcranial electrical stimulation to enhance learning and automaticity in mathematical domains have reverse effects depending on the area of the brain being stimulated.[64]

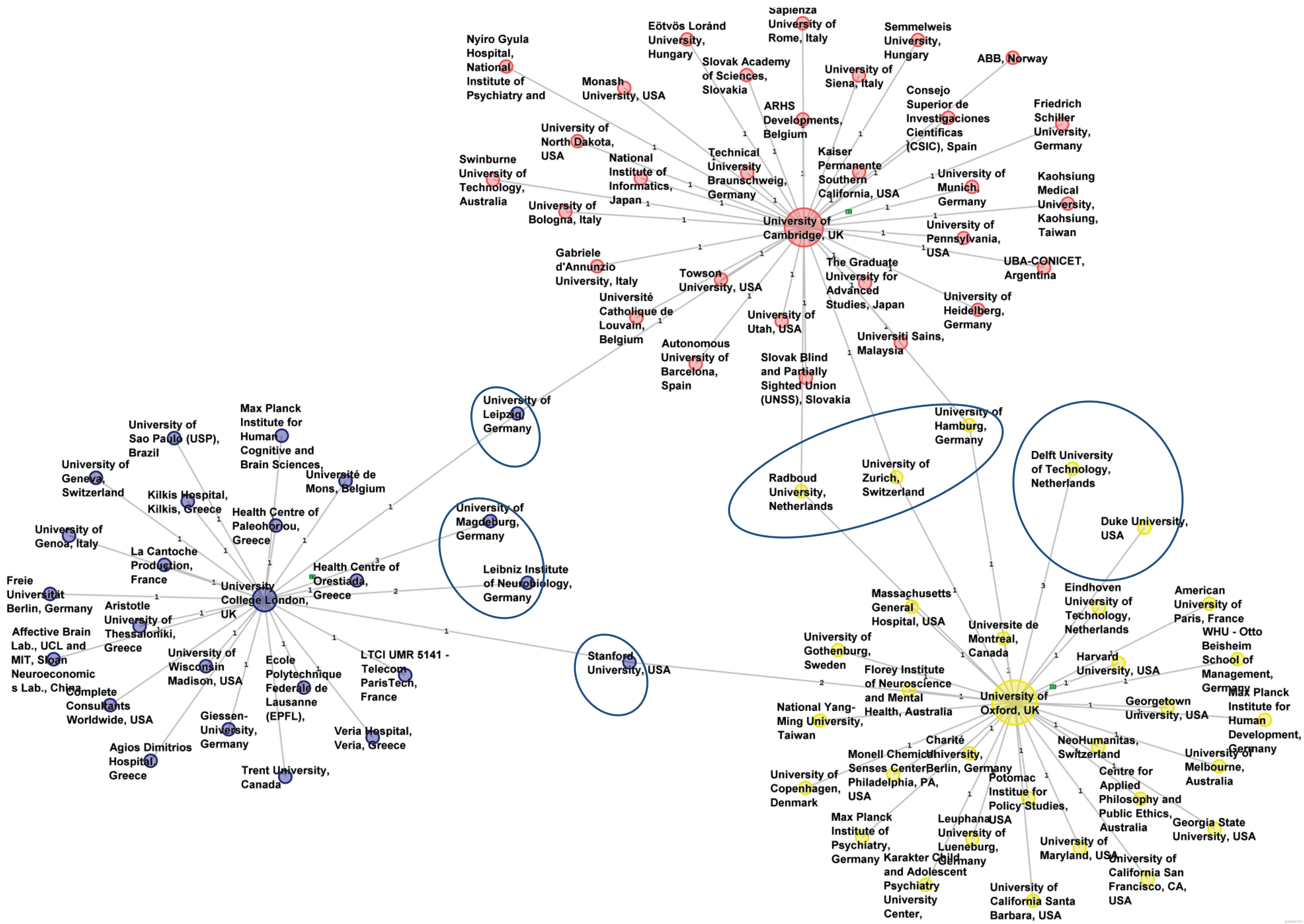

Figure 16. UK: Top Affiliations, International Collaborations, Part 1

The University College of London has three publications with the University of Magdeburg, Germany, two of which are co-publications with Leibniz Institute of Neurobiology, Germany. The first collaboration between the University of Magdeburg and Leibniz Institute of Neurobiology presents results that indicate that human detection of lower-intensity visual targets is enhanced with the co-occurrence of auditory stimuli.[65] The second co-publication also included collaboration with the University of Leipzig, Germany and studied the positive impact of viewing images of novel scenes on hippocampus-dependent memory.[66] The last co-publication includes collaboration with Giessen University, Germany and focuses on the use of rewards to enhance episodic memory with implications for dopaminergic neuromodulation.[67]

The University of Cambridge has also collaborated with the University of Leipzig, Germany on the effects of modafinil and methylphenidate on visual attention capacity with implications for predicting the enhancing and detrimental effects of these stimulants on both healthy and cognitively deficient people.[68]

Both the University of Oxford and University of Cambridge have separate publications with the University of Hamburg, Germany, Radboud University, Netherland, and the University of Zurich, Switzerland. Table 4 summarizes the research in these collaborations.

Table 4. Summary of Select UK Collaborations

Collaborators	Topic
University of Cambridge – University of Hamburg, Germany	Use of nano-optomechanical systems (NOMS) as a human enhancing solution to tactile perception for both the visually impaired and general public. [69]
University of Cambridge – Radboud University, Netherland – UBA-CONICET, Argentina	Cognitive enhancing effects of voluntary exercise, caloric restriction and environmental enrichment. [70]
University of Cambridge – University of Zurich, Switzerland – CAMEO, UK	The need to consider the forms of cognitive enhancement that may be acceptable for which groups, under what conditions, and by what methods.[71]
University of Oxford – University of Hamburg, Germany – Charité University, Germany – Max Planck Institute of Psychiatry, Germany – Monell Chemical Senses Center, USA – University of Maryland, USA – National Yang-Ming University, Taiwan – Max Planck Institute for Human Development, Germany	Part of a special issue entitled Cognitive Enhancers, this article discusses the importance of considering the ethical issues of non-pharmaceutical cognitive enhancers which appear, in many cases, to be more effective than pharmaceutical enhancers.[72]
University of Oxford – Radboud University, Netherland – Karakter Child and Adolescent Psychiatry University Center, Netherland – University of California San Francisco, USA	Reports that methylphenidate amplifies salience of task-relevant information at the level of the stimulus category.[73]
University of Oxford – University of Zurich, Switzerland – Université de Montreal, Canada – NeoHumanitas, Switzerland	Provides definitions and solutions to the problems of a lack of agreed upon definition of human enhancement and insufficient grounds for assessing the morality of human enhancement.[74]

Figure 17 shows the collaboration networks for the University of Manchester and Imperial College of London. Neither have repeat nor shared collaborations.

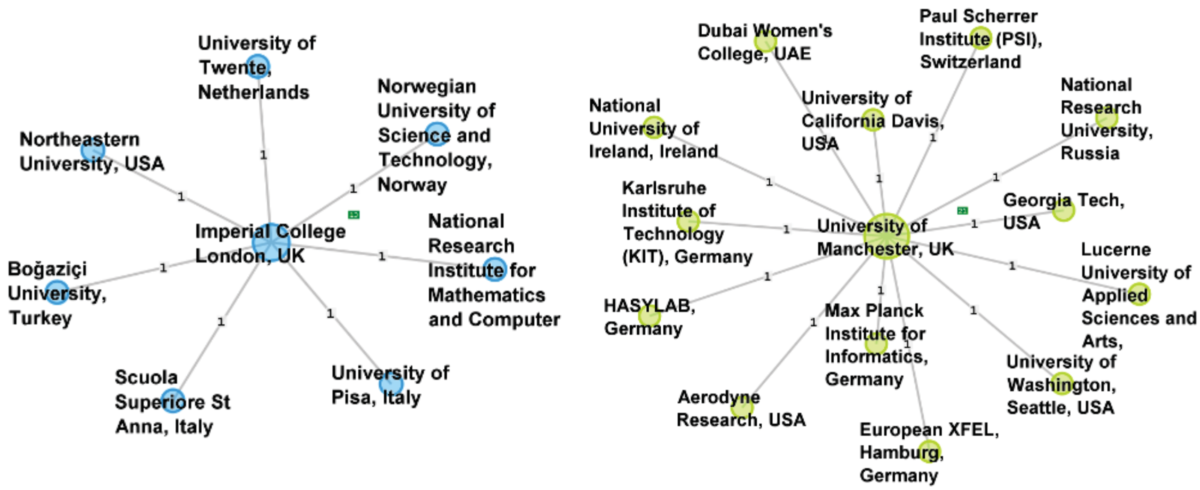

Figure 17. UK Top Affiliations, International Collaborations, Part 2

3.6.1.4 Switerland

The top five Swiss affiliations have 68 publications, 30 with collaborations, 26 of which are with 61 different international collaborators. Figure 18 presents the number of international collaborators for each of the top five Swiss affiliations.

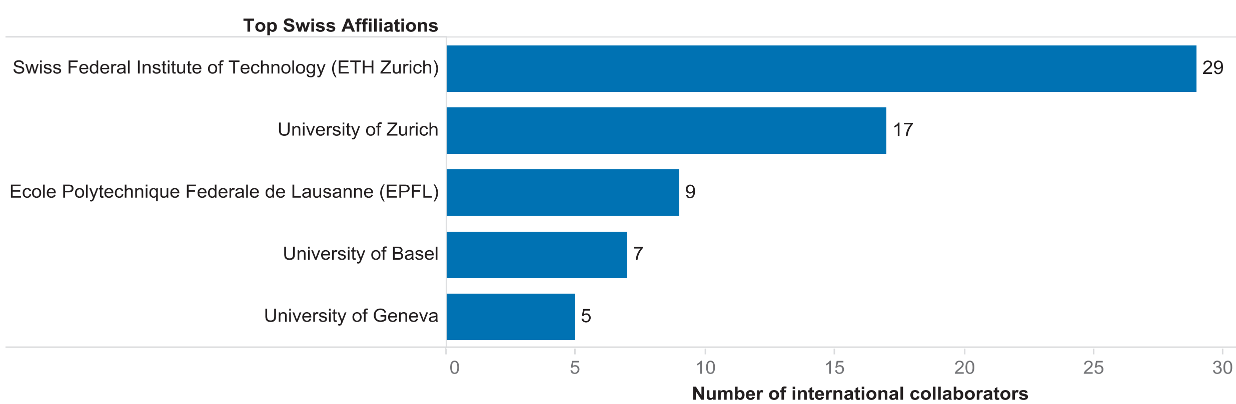

Figure 18. Swiss Top Affiliations, Number of International Collaborators

While the Swiss Federal Institute of Technology is the only Swiss affiliation with more than one paper with the same affiliation, Switzerland has an interesting pattern of collaborations with international collaborators in that four of the top five Swiss affiliations are collaborating with at least one other international collaborator of the other four top Swiss affiliations. Only the University of Basel does not share an international collaborator. Figure 18 below shows these collaborations. The image file and the supporting raw data file are provided as Attachments 13 and 14 with this report.

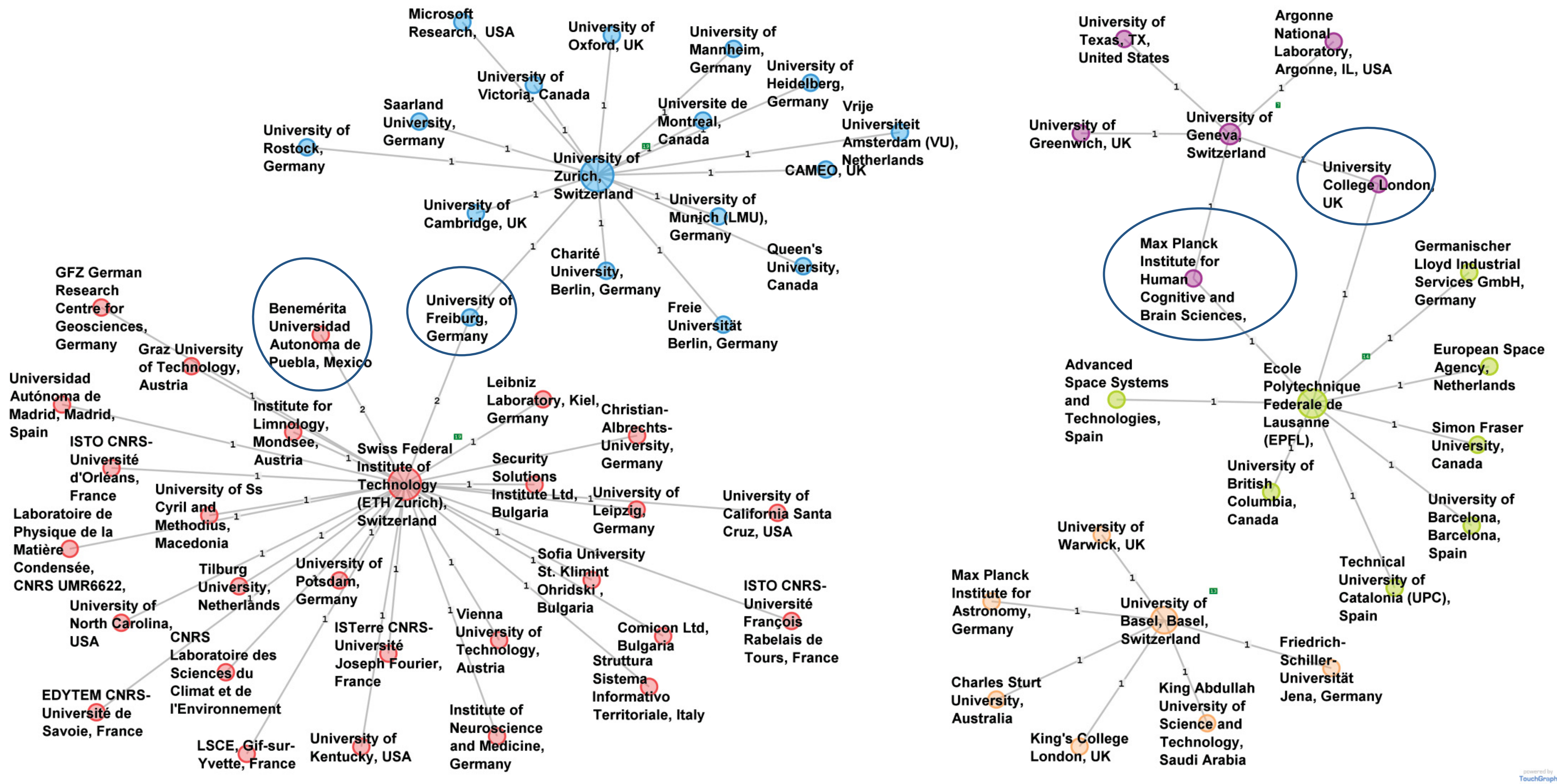

Figure 19. Switzerland: Top Affiliations, International Collaboration

The Swiss Federal Institute of Technology has co-published two papers about the positive effects of Gaussian noise on human motor and sensorimotor performance with both Benemérita Universidad Autónoma de Puebla, Mexico and the University of Freiburg, Germany.[75,76] The first of the two publications is co-published with the Institute of Neuroscience and Medicine, Germany.

The University of Zurich also has a co-publication with the University of Freiburg, Germany that looks at the effects of emotional stimuli on memory tasks and found enhanced reactivity in affectively unstable individuals.[77]

Both the Ecole Polytechnique Federale de Lausanne (EPFL) and the University of Geneva have collaborated with the University College of London, UK and the Max Planck Institute for Human Cognition, Germany on a single 2015 publication which argues that real-time functional magnetic resonance imaging neurofeedback can be a powerful tool for cognitive enhancement in the domains of perception, motor performance and memory.[78]

3.7 Editorial Boards

Table 5 presents a basic view of the top journals and conferences in the field of human cognition.[h] An Excel sheet with the associated editors is provided as Attachment 15 with this report as a potential additional means of identifying experts in the field.

Table 5. Top Journals and Conferences

Top Sources	# Publications
Lecture Notes in Computer Science	126
Proceedings of SPIE - the International Society for Optics and Photonics	52
Psychopharmacology	46
ACM International Conference Proceedings Series	45
Neuropharmacology	41
Journal of Medical Ethics: Journal of the Institute of Medical Ethics	37
PLoS ONE	32
Proceedings of the Human Factors and Ergonomics Society	32
Frontiers in Systems Neuroscience	28
IEEE/RSJ International Conference on Intelligent Robots and Systems	28
Neuroethics	28
Dissertation Abstracts International: Section B: The Sciences and Engineering	25
Behavioural Brain Research	23
ACM Conference on Human Factors in Computing Systems Proceedings	20
Jane's Defense Weekly	20
Bioethics	18
Communications in Computer and Information Science	17
Pharmacology	16

[h] The variant forms of the names of these sources were too inconsistent for the tool to automatically clean. A quick manual cleaning of the top sources was completed by the analyst. As such, this list may not be definitive but does reflect most of the top sources in the dataset.

4 CONCLUSIONS

This scientometric study was commissioned to provide an overview of international research activity and collaboration networks in the field of human optimization. This study will assist DRDC in facilitating two workshops that are being planned to bring together experts in the field.

The results of this study show that international research is primarily focused on *Computational/ Cognitive Issues* (6,039 publications) and *Physiological Issues* (5,176) followed by *Automation/Robotics* (3,183) and *Ethics* (2,976). At first glance, this is a contrast to the Canadian landscape which was more evenly dispersed between the four metagroups, with *Ethics* holding a slight majority. That being said, the categorization of subject groups did shift between the two studies as the conceptual framework for analyzing the data became richer with more data. These changes were approved by the client and are thus still in line with an expert understanding of the field. To truly compare the Canadian and international datasets, a re-grouping of the Canadian set would be required to confirm this distinction. Then, further analysis would be recommended to compare Canada's propensity to publish in the *Ethics* metagroup with each international country's propensity to assess if Canada truly has an edge. The relative specialization index is one method that can be used for this comparison.

An additional metagroup called *Means of Enhancement* was created for this study to provide a first step in summarizing the methods that are used for human optimization. An additional approach to further analyzing the data would be to examine the application areas of human optimization research. Undoubtedly, many of the areas are military in nature, yet other application areas include the judicial system, medicine and athletics. While not analyzed in this report, the dataset also includes a preliminary list of close to 20 specific drugs that are being used for the purposes of human optimization. Additional analysis of and/or searching on this data might also be insightful.

The number of international authors with at least two publications in the field is close to 3,000 and the top 50, all of whom have at least 9 publications, has been provided as an attachment to this report. This list is, for the most part, missing author names from such countries as China, Japan, Taiwan, Korea, Singapore, Hong Kong, Malaysia etc. due to technical challenges with the main database from which the references came. In effect, the database merged all authors with names such as Li, Y. regardless of whether the publication was written by Yuan Li or Yufeng Li. Unfortunately, there was no way to separate the individual authors in the analysis tool despite being able to confirm that the authors were different individuals from different institutions. As such, it is recommended to find another means of identifying authors from these countries who may also have a high number of publications.

The collaboration networks of the top four collaborating countries are widely dispersed in that there are few repeat collaborations. There is, however, some evidence that a number of the publications had quite a few international collaborators working all together. This is particularly evident with the selected UK collaborations described in Table 4, which show numerous collaborators from both the UK and elsewhere working on a single paper. There was some evidence that the top institutions were separately collaborating with the same international collaborators, but again, not repeatedly. This was seen in the US, UK and Switzerland, but not Germany. The cause of these collaboration patterns is not clear. Additional mapping of a larger number of each country's top affiliations and/or of other countries' collaboration networks might reveal if this is indeed a consistent pattern across the international landscape.

In order to identify international researchers to invite to participate in the IRDS workshops on human optimization, it is recommended that researchers from the US, Switzerland and Germany be approached. The US has a very active research community with the highest number of top authors. There are already a high number of collaborations with Canadian researchers, making this an obvious choice for further formalizing collaborative relationships. Furthermore, many of the US top affiliations are military-based and could thus provide particular insights of interest to DRDC. Switzerland is the top collaborator in the dataset as well as the country with the highest growth rate in recent years. Canada currently only has eight collaborations with Switzerland, yet Switzerland's position in the field makes it an interesting country with whom to pursue additional relationships. Finally, Germany, the second most prolific country in the dataset, is Canada's second most frequent collaborator and existing relationships, coupled with Germany's expertise, make it another ideal candidate for invitation.

Geographic-based collaboration maps were developed and shown to the client. Unfortunately, given how many how many different one-off collaborations there were on the map, the tools available to the NRC are insufficient insufficient to provide the level of clarity that was desired.

Figure 10 is provided as raw data with which other tools can be used to provide clearer maps.

Unlike the Canadian report which recommended additional searching in selected fields such as load carriage and soldiers, adaptation for extreme environments and enhanced vision (to name a few) in order to gather a richer dataset, it is felt that the search strategy was sufficiently effective in these areas. Additional searching may still be warranted in wearables, wound sensing, self-decontamination aids, and autonomous systems and trust. The challenge is that many of these subtopics do not explicitly make connections to human optimization in the keywords or abstracts despite being related to human enhancement in some regard. On the other hand, searching with the keyword *optimization* led to a significant number of false hits that were not specifically related to *human* optimization (again due to weakness in Scopus's search function). This problem was not nearly as evident in the smaller Canadian set. These articles (in the thousands) needed to be manually removed by keyword and abstract review. The challenge in this field is that the search needs to be broad enough to capture as many sub-topics (e.g. 114) as possible while minimizing false hits. Finally, in addition to more searching in specific sub topics, it is recommended, to the extent possible, to search classified data to expand the results of this study.

5 REFERENCES

1. Fuchs S, Carpenter A, Carroll M, Hale K. A hierarchical adaptation framework for adaptive training systems. *Foundations of Augmented Cognition. Directing the Future of Adaptive Systems. Proceedings 6th International Conference, FAC 2011. Held as Part of HCI International 2011.* 2011:413-421.
2. Gorman JC, Martin MJ, Dunbar TA, Stevens RH, Galloway T. Analysis of semantic content and its relation to team neurophysiology during submarine crew training. *Foundations of Augmented Cognition. 7th International Conference, AC 2013. Held as Part of HCI International 2013. Proceedings.* 2013:143-152.
3. Coyne JT, Baldwin C, Cole A, Sibley C, Roberts DM. Applying real time physiological measures of cognitive load to improve training. *Foundations of Augmented Cognition. Neuroergonomics and Operational Neuroscience. Proceedings 5th International Conference, FAC 2009. Held as part of HCI International 2009.* 2009:469-478.
4. Sullivan JA. *Assessing Neurophysiologic Markers for Training and Simulation to Develop Expertise in Complex Cognitive Tasks*: Non Paid ADAS;2010.
5. Hyuk O, Hatfield BD, Jaquess KJ, et al. A composite cognitive workload assessment system in pilots under various task demands using ensemble learning. *Foundations of Augmented Cognition. 9th International Conference, AC 2015, held as part of HCI International 2015. Proceedings: LNCS 9183.* 2015:91-100.
6. Ayaz H, Crawford P, Curtin A, et al. Differential Prefrontal Response during Natural and Synthetic Speech Perception: An fNIR Based Neuroergonomics Study. *Foundations of Augmented Cognition. 7th International Conference, AC 2013. Held as Part of HCI International 2013. Proceedings.* 2013:241-249.
7. Hernandez-Meza G, Slason L, Ayaz H, Craven P, Oden K, Izzetoglu K. Investigation of Functional Near Infrared Spectroscopy in Evaluation of Pilot Expertise Acquisition. *Foundations of Augmented Cognition. 9th International Conference, AC 2015, held as part of HCI International 2015. Proceedings: LNCS 9183.* 2015:232-243.
8. Estepp JR, Klosterman SL, Christensen JC. An assessment of non-stationarity in physiological cognitive state assessment using artificial neural networks. *2011 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society.* 2011:6552-6555.
9. Weichao G, Pengfei Y, Xinjun S, Honghai L, Xiangyang Z. A wireless wearable sEMG and NIRS acquisition system for an enhanced human-computer interface. *2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC).* 2014:2192-2197.
10. Gregory FD, Liyi D. Multisensory Information Processing for Enhanced Human-Machine Symbiosis. *Human Interface and the Management of Information Information and Knowledge Design. 17th International Conference, held as part of HCI International 2015. Proceedings: LNCS 9172.* 2015:354-365.
11. Hoeckelmann M, Rudas IJ, Fiorini P, Kirchner F, Haidegger T. Current capabilities and development potential in surgical robotics. *International Journal of Advanced Robotic Systems.* 2015;12.
12. Chee-Kong C, Nguyen BP, Rong W. Development of a cognitive engine for balancing automation and human control of surgical robotic system. *2014 11th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI). Proceedings.* 2014:13-17.
13. Peschka A, Berger T, Maier T, Scholz M, Lüth TC, Strauß G. Evaluation of a Micro-Manipulator for Middle Ear Surgery: A Preclinical Trial. *Laryngo- Rhino- Otologie.* 2015.

14. Caproni M, Orihuela-Espina F, James DRC, et al. An analysis framework for near infrared spectroscopy based brain-computer interface and prospective application to robotic surgery. In: proceedings from 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 20092009; St. Louis, MO.
15. Widmer A, Hu Y. Effects of the alignment between a haptic device and visual display on the perception of object softness. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans.* 2010;40(6):1146-1155.
16. McWilliams A. *Medical Robotics and Computer-Assisted Surgery: The Global Market*. 2011. http://www.bccresearch.com/market-research/healthcare/robotics-computer-surgery-market-hlc036d.html.
17. Koops BJ, Lüthy CH, Nelis A, Sieburgh C, Jansen JPM, Schmid MS. *Engineering the human: Human enhancement between fiction and fascination.* Vol 9783642350962: Springer-Verlag Berlin Heidelberg; 2013.
18. Gasson MN. ICT implants: The invasive future of identity? In: Fischer-Hubner SFH, Martucci ML, Duquenoy PD, Zuccato AZ, eds. *IFIP International Federation for Information Processing.* Vol 2622008:287-295. http://www.scopus.com/inward/record.url?eid=2-s2.0-45949093499&partnerID=40&md5=94022d4ee5429af5f90859f0a5411c04.
19. Metzinger TK. Neuroethics of pharmaceutical cognitive enhancement: The first ten years current problems and practical guiding principles. *Fortschritte der Neurologie Psychiatrie.* 2012;80(1):36-43.
20. Chandler JA. Autonomy and the unintended legal consequences of emerging neurotherapies. *Neuroethics.* 2013;6(2):249-263.
21. de Sio FS, Faulmüller N, Vincent NA. How cognitive enhancement can change our duties. *Frontiers in Systems Neuroscience.* 2014;8(JULY).
22. Lev O. Biomedical cognitive enhancements: Coercion, competition and inducements. *Law and Ethics of Human Rights.* 2015;9(1):69-89.
23. Franke AG, Northoff R, Hildt E. The Case of Pharmacological Neuroenhancement: Medical, Judicial and Ethical Aspects from a German Perspective. *Pharmacopsychiatry.* 2015;48(7):256-264.
24. McGee EM. Neuroethics and implanted brain machine interfaces. *Uberveillance and the Social Implications of Microchip Implants: Emerging Technologies*: IGI Global; 2013:351-365.
25. Forlini C, Racine E. Added Stakeholders, Added Value(s) to the Cognitive Enhancement Debate: Are Academic Discourse and Professional Policies Sidestepping Values of Stakeholders? *AJOB Primary Research.* 2012;3(1):33-47.
26. McVeigh J, Evans-Brown M, Bellis MA. Human enhancement drugs and the pursuit of perfection. *Adicciones.* 2012;24(3):185-190.
27. Vargo EJ, James RA, Agyeman K, et al. Perceptions of assisted cognitive and sport performance enhancement among university students in England. *Performance Enhancement and Health.* 2014;3(2):66-77.
28. Outram S, Stewart B. Enhancement drug use in society and in sport: the science and sociology of stimulant use and the importance of perception. *Sport in Society.* 2013;16(6):789-804.
29. Sefiha O. Bike racing, neutralization, and the social construction of performance-enhancing drug use. *Contemporary Drug Problems: An Interdisciplinary Quarterly.* 2012;39(2):213-245.
30. Sefiha O. *Deviance, sport, and social control: A cross-cultural investigation of contemporary doping narratives*. US: ProQuest Information & Learning; 2010.
31. Partridge B, Lucke J, Hall W. A Comparison of Attitudes Toward Cognitive Enhancement and Legalized Doping in Sport in a Community Sample of Australian Adults. *AJOB Primary Research.* 2012;3(4):81-86.

32. Mache S, Eickenhorst P, Vitzthum K, Klapp BF, Groneberg DA. Cognitive-enhancing substance use at German universities: Frequency, Reasons and gender differences. *Wiener Medizinische Wochenschrift.* 2012;162(11-12):262-271.
33. Sattler S, Wiegel C. Cognitive test anxiety and cognitive enhancement: The influence of students' worries on their use of performance-enhancing drugs. *Substance Use and Misuse.* 2013;48(3):220-232.
34. Hildt E, Lieb K, Franke AG. Life context of pharmacological academic performance enhancement among university students—A qualitative approach. *BMC Medical Ethics.* 2014;15.
35. Ilieva I, Boland J, Farah MJ. Objective and subjective cognitive enhancing effects of mixed amphetamine salts in healthy people. *Neuropharmacology.* 2013;64:496-505.
36. Farah MJ. The unknowns of cognitive enhancement: Can science and policy catch up with practice? *Science.* 2015;350(6259):379-380.
37. Ricciardi E, Handjaras G, Bernardi G, Pietrini P, Furey ML. Cholinergic enhancement reduces functional connectivity and BOLD variability in visual extrastriate cortex during selective attention. *Neuropharmacology.* 2013;64:305-313.
38. Beer AL, Vartak D, Greenlee MW. Nicotine facilitates memory consolidation in perceptual learning. *Neuropharmacology.* 2013;64:443-451.
39. Kadosh RC. Bertelson award lecture at the 18th ESCOP conference, Budapest, Hungary: Modulating and enhancing cognition using brain stimulation: Science and fiction. *European Journal of Cognitive Psychology.* 2015;27(2):141-163.
40. Madan CR. Augmented memory: A survey of the approaches to remembering more. *Frontiers in Systems Neuroscience.* 2014;8(MAR).
41. Lapenta OM, Valasek CA, Brunoni AR, Boggio PS. An ethical discussion of the use of transcranial direct current stimulation for cognitive enhancement in healthy individuals: A fictional case study. *Psychology and Neuroscience.* 2014;7(2):175-180.
42. Luber B, Lisanby SH. Enhancement of human cognitive performance using transcranial magnetic stimulation (TMS). *NeuroImage.* 2014;85(Part 3):961-970.
43. Wokke ME, Talsma LJ, Vissers ME. Biasing neural network dynamics using non-invasive brain stimulation. *Frontiers in Systems Neuroscience.* 2015;8(JAN).
44. Morales-Quezada L, Cosmo C, Carvalho S, et al. Cognitive effects and autonomic responses to transcranial pulsed current stimulation. *Experimental Brain Research.* 2014;233(3):701-709.
45. Sarkar A, Dowker A, Kadosh RC. Cognitive enhancement or cognitive cost: Trait-specific outcomes of brain stimulation in the case of mathematics anxiety. *Journal of Neuroscience.* 2014;34(50):16605-16610.
46. Enriquez-Geppert S, Huster RJ, Herrmann CS. Boosting brain functions: Improving executive functions with behavioral training, neurostimulation, and neurofeedback. *International Journal of Psychophysiology.* 2013;88(1):1-16.
47. Chi RP, Snyder AW. Brain stimulation enables the solution of an inherently difficult problem. *Neuroscience Letters.* 2012;515(2):121-124.
48. Dresler M, Sandberg A, Ohla K, et al. Non-pharmacological cognitive enhancement. *Neuropharmacology.* 2013;64:529-543.
49. DeMarco JP, Ford PJ. Neuroethics and the Ethical Parity Principle. *Neuroethics.* 2014;7(3):317-325.
50. Levy N, Savulescu J. The Neuroethics of Transcranial Electrical Stimulation. *The Stimulated Brain: Cognitive Enhancement Using Non-Invasive Brain Stimulation*: Elsevier Inc.; 2014:499-521.
51. Dubljević V. Neurostimulation devices for cognitive enhancement: Toward a comprehensive regulatory framework. *Neuroethics.* 2015;8(2):115-126.

52. Maslen H, Douglas T, Kadosh RC, Levy N, Savulescu J. Do-it-yourself brain stimulation: A regulatory model. *Journal of Medical Ethics: Journal of the Institute of Medical Ethics.* 2015;41(5):413-414.
53. Hemond C, Brown RM, Robertson EM. A distraction can impair or enhance motor performance. *Journal of Neuroscience.* 2010;30(2):650-654.
54. Levasseur-Moreau J, Brunelin J, Fecteau S. Non-invasive brain stimulation can induce paradoxical facilitation. Are these neuroenhancements transferable and meaningful to security services? *Frontiers in Human Neuroscience.* 2013;7:449.
55. Vachon-Presseau E, Roy M, Martel MO, et al. The two sides of pain communication: Effects of pain expressiveness on vicarious brain responses revealed in chronic back pain patients. *Journal of Pain.* 2013;14(11):1407-1415.
56. McClernon CK, McCauley ME, O'Connor PE, Warm JS. Stress training improves performance during a stressful flight. *Human Factors.* 2011;53(3):207-218.
57. Lew S, Wolters C, Anwander A, Makeig S, MacLeod R. Low resolution conductivity estimation to improve source localization. In: proceedings from Proceedings of the 15th International Conference on Biomagnetism: New Frontiers in Biomagnetism. 2007; Vancouver, BC, Canada.
58. Lew S, Wolters CH, Anwander A, Makeig S, MacLeod RS. Improved EEG source analysis using low-resolution conductivity estimation in a four-compartment finite element head model. *Human Brain Mapping.* 2009;30(9):2862-2878.
59. Schelle KJ, Faulmüller N, Caviola L, Hewstone M. Attitudes toward pharmacological cognitive enhancement—A review. *Frontiers in Systems Neuroscience.* 2014;8.
60. Maslen H, Santoni de Sio F, Faber N. With cognitive enhancement comes great responsibility? *Responsible Innovation 2: Concepts, Approaches, and Applications*: Springer International Publishing; 2015:121-138.
61. Sandberg A, Sinnott-Armstrong W, Savulescu J. Cognitive Enhancement in Courts. *Oxford Handbook of Neuroethics*: Oxford University Press; 2012.
62. Sandberg A, Savulescu J. The memory of jurors: Enhancing trial performance. In: Sinnott-Armstrong WP, ed. *Memory and law*. New York, NY, US: Oxford University Press; 2013:213-229.
63. Benedikter R, Giordano J, Fitzgerald K. The future of the self-image of the human being in the Age of Transhumanism, Neurotechnology and Global Transition. *Futures.* 2010;42(10):1102-1109.
64. Iuculano T, Kadosh RC. The mental cost of cognitive enhancement. *The Journal of Neuroscience.* 2013;33(10):4482-4486.
65. Noesselt T, Tyll S, Boehler CN, Budinger E, Heinze HJ, Driver J. Sound-induced enhancement of low-intensity vision: Multisensory influences on human sensory-specific cortices and thalamic bodies relate to perceptual enhancement of visual detection sensitivity. *Journal of Neuroscience.* 2010;30(41):13609-13623.
66. Fenker DB, Frey JU, Schuetze H, Heipertz D, Heinze HJ, Duzel E. Novel scenes improve recollection and recall of words. *Journal of Cognitive Neuroscience.* 2008;20(7):1250-1265.
67. Wittmann BC, Dolan RJ, Düzel E. Behavioral specifications of reward-associated long-term memory enhancement in humans. *Learning and Memory.* 2011;18(5):296-300.
68. Finke K, Dodds CM, Bublak P, et al. Effects of modafinil and methylphenidate on visual attention capacity: A TVA-based study. *Psychopharmacology.* 2010;210(3):317-329.
69. Campo EM, Roig J, Roeder B, et al. Nano opto-mechanical systems (NOMS) as a proposal for tactile displays. *Nano-Opto-Mechanical Systems (NOMS).* 2011;8107:81070H.
70. Kent BA, Oomen CA, Bekinschtein P, Bussey TJ, Saksida LM. Cognitive enhancing effects of voluntary exercise, caloric restriction and environmental enrichment: A role for adult

hippocampal neurogenesis and pattern separation? *Current Opinion in Behavioral Sciences.* 2015;4:179-185.

71. Sahakian BJ, Bruhl AB, Cook J, et al. The impact of neuroscience on society: Cognitive enhancement in neuropsychiatric disorders and in healthy people. *Philosophical Transactions of the Royal Society B: Biological Sciences.* 2015;370(1677).
72. Dresler M, Sandberg A, Ohla K, et al. Non-pharmacological cognitive enhancement. *Neuropharmacology.* 2013;64:529-543.
73. ter Huurne N, Fallon SJ, van Schouwenburg M, et al. Methylphenidate alters selective attention by amplifying salience. *Psychopharmacology.* 2015;232(23):4317-4323.
74. Roduit JAR, Menuz V, Baumann H. Human enhancement: Living up to the ideal human. *Global Issues and Ethical Considerations in Human Enhancement Technologies*: IGI Global; 2014:54-66.
75. Trenado C, Mikulić A, Manjarrez E, et al. Broad-band Gaussian noise is most effective in improving motor performance and is most pleasant. *Frontiers in Human Neuroscience.* 2014;8(1 FEB).
76. Trenado C, Mendez-Balbuena I, Manjarrez E, et al. Enhanced corticomuscular coherence by external stochastic noise. *Frontiers in Human Neuroscience.* 2014;8(MAY).
77. Prehn K, Schulze L, Rossmann S, et al. Effects of emotional stimuli on working memory processes in male criminal offenders with borderline and antisocial personality disorder. *World Journal of Biological Psychiatry.* 2013;14(1):71-78.
78. Scharnowski F, Weiskopf N. Cognitive enhancement through real-time fMRI neurofeedback. *Current Opinion in Behavioral Sciences.* 2015;4:122-127.

APPENDIX A: ATTACHMENTS

The following files have been provided as attachments to the recipients of this report.

Filename	Description
1. Ho2 – Metagroup Membership.xlsx	Lists subject groups in each of the four metagroups
2. Ho2 – Research Clusters Final.png	Shows the clusters within the subject groups. Same as Figures 3
3. Ho2 – Full Research Momentum Chart.png	Maps the research momentum of all 114 groups in all four quadrants
4. Ho2 – Top 50 International Authors Contact.xlsx	Provides contact information, area of expertise, and notes when issues arose regarding affiliation
5. Ho2 – Top Affiliations and Areas of Expertise	Provides the areas of expertise (based on top groups and metagroups) for the top affiliations presented in Figure 6
6. Ho2 – Country Collaborations – Raw Data.xlsx	Raw data used to create country collaboration matrix in Figure 10
7. Ho2 – US Top Affiliation Collaborations.png	US Top Affiliation Collaborations. Same as Figure 12
8. Ho2 – US Top Affiliation Collaborations – Raw Data.xlsx	Raw Data used to create Figure 12
9. Ho2 – German Top Affiliation Collaborations.png	German Top Affiliation Collaborations. Same as Figure 14
10. Ho2 – German Top Affiliation Collaborations – Raw Data.xlsx	Raw Data used to create Figure 14
11. Ho2 – UK Top Affiliation Collaborations.png	UK Top Affiliation Collaborations. Same as Figure 16 and 17
12. Ho2 – UK Top Affiliation Collaborations – Raw Data.xlsx	Raw Data used to create Figure 16 and 17
13. Ho2 – Swiss Top Affiliation Collaborations.png	Swiss Top Affiliation Collaborations. Same as Figure 19
14. Ho2 – Swiss Top Affiliation Collaborations – Raw Data.xlsx	Raw Data used to create Figure 19
15. HE – Editorial Boards of Top Sources.xlsx	A list of editors for the top sources in Table 5

APPENDIX B: METHODOLOGY

Searches

To address the key questions in this project, a broad search on human optimization was conducted in several databases including *Scopus, Inspec, Compendex, PsychInfo* and *National Technical Information Service (NTIS)* between 2005-2015. The initial search resulted in a dataset of close to 26,000 international publications. After removing duplicates, the dataset was searched for pre-defined topics for exclusion (e.g. animals, children, diagnosis etc.) and these records were removed. Additionally, a list of 2,634 titles for potential omission was provided to the client for review and selected records were removed. Through the grouping process roughly 500 more articles were reviewed by the analyst and necessary omissions were made resulting in a final dataset of 7,656 relevant international publications.

Table 6 lists the concepts included in the search. These terms were used in multiple combinations with various Boolean operators depending on the database that was searched. In the end, the majority of the final publications were found in Scopus.

Table 6. Search Terms

Optimize	Human	Performance
Improve	Human	Effectiveness
Increase	Cognitive	Performance
Augment	Soldier	Cognition
Enhance	Individual	
Optimize	Personal	
	Personnel	
	Pilot	
	Astronaut	
	Aircrew	
	Troops	
	Special operations	
	Flight surgeon	
	Infantry	
	Military	

Analysis

All references were downloaded into VantagePoint software for analysis. VantagePoint enables the creation of various groupings, statistical analyses, matrices, graphs, and cross-correlations to analyze the data and profile the activities of the major players.

Keywords, classification codes, index keywords, key phrase identifiers, subject headings, author keywords and words and phrases extracted by natural language processing of titles and abstracts were merged together to facilitate subject analysis (hereafter referred to as keywords). Keywords were then organized into subject groups through a variety of steps. First, the table of metagroups provided by the client was used to create subject groups. Any additional groups that were created in the Canadian study were also searched in the international study. Keywords (that had at least five titles associated with them) that were not yet grouped were reviewed and added to existing or new groups. The client and analysts reviewed the keywords in every group and identified terms for exclusion and merged or split groups as appropriate. The metagroups were created by first replicating the metagroups in the Canadian study and then the client reviewed, made changes and placed any new groups into the appropriate metagroups.

Different analytical tools were used to generate graphs based on statistical operations performed in VantagePoint. TouchGraph software was used for cluster analysis and visualization of the subject groups while Tableau software was used to generate bubble graphs.

R&D Momentum

The R&D Momentum indicator is designed to identify rapidly rising subjects with relatively few publications. The challenge of identifying such subjects lies with the publication volume as a confounding factor, for their rapid growth and evolution is dwarfed by the high volume of established subjects. Specifically, the notion of "emerging" consists not only of a sharply rising trend line but also of a small footprint in the domain of interest. A *relatively* small footprint is the reason emerging subjects are often overlooked until their disruptive impacts become obvious. In the Momentum indicator, the two parameters correspond to (1) growth rate, which is the slope of a subject's trend line (right-left axis), and (2) volume, which is the cumulated total number of publications (vertical axis).

Once growth rate and volume are separated, a two-dimensional coordinate can be used to plot a group of subjects. To do so, the two parameters have to be normalized with z-scores. The normalization process converts two sets of values in different units into the same measure by means of standard deviation, which also standardizes the variations for each of the two parameters. The four-quadrant visualization provides a structured view of the relative position of these subjects within the group.